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Sequence stratigraphy and depositional systems in the Upper Cretaceous (Cenomanian) Woodbine Group, Anderson and Cherokee Counties, Texas

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by

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Abstract

Sequence stratigraphy and depositional systems in the Upper Cretaceous (Cenomanian) Woodbine Group, Anderson and Cherokee Counties, Texas

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The University of Texas at Austin, 2016

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The Woodbine Group of the East Texas Basin has attracted considerable interest because of its remaining petroleum resource in the deeper Woodbine pay. Recent estimate of the remaining petroleum resources in the East Texas field is approximately 1.58 billion stock tank barrels (BSTB) (Wang et al., 2008). However, expected ultimate recovery is limited by reservoir compartmentalization controlled by a complex stratigraphic framework. The purpose of this study is to define depositional systems and construct the stratigraphic framework of the Woodbine Group in Anderson and Cherokee Counties to provide the geologic context for characterizing remaining reserves. This study integrates core data and log data from closely spaced wireline logs (~1000 wells), using a chronostratigraphic method, to define sequence stratigraphic units. The stratigraphic framework of the Woodbine succession in the study area is composed of a

maximum of 14 cycles in the basin axis, decreasing to a minimum of 3 cycles eastward to the Sabine Uplift and a minimum of 6 cycles westward to the out crop belt. The Woodbine succession is overlain by impermeable deposits of the Eagle Ford Shale and the Austin chalk as hydrocarbon seals.

The complexity and heterogeneity of sandstone bodies in the Woodbine Group are largely controlled by depositional origin. Woodbine highstand and lowstand sequences display great variations in the depositional systems. The highstand deposits are composed mostly of fluvial dominated delta deposits that consist of distributary-channel, crevasse-splay, and delta-front deposits. Gamma-ray and spontaneous potential responses for these highstand deposits are upward-coarsening and serrate. In contrast, Woodbine lowstand deposits are mainly composed of coarse-grained sandstones of incised valley fills, reflecting relative base-level fall. These lowstand deposits, truncate older highstand deposits and are inferred from planar-based and blocky serrate log responses. Furthermore, highstand and lowstand deposits are overlain by transgressive deposits. These transgressive deposits are characterized by upward-fining log response, reflecting relative base-level rise. Correlation of sequence stratigraphic surfaces, sandstone-body stacking patterns and reservoir complexity inferred from gross-sandstone maps can lead to new exploration targets in the Woodbine Group in the southern part of the East Texas Basin.

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Chapter 1: Introduction

The East Texas Basin consists of many prolific oil fields such as East Texas oil field, which is the second largest oil field in the United States in terms of original oil in place (OOIP), consisting of 7.03 billion stock tank barrels of oil (BSTB) (Wang et al., 2008). Discovered in 1930, approximately 5.42 BSTB of oil have been produced from the Upper Cretaceous Woodbine sandstones in the field. The Woodbine Group in the East Texas Basin is composed of shallow-marine and fluvial siliciclastic deposits. The depositional environments of the Woodbine Group vary geographically as well as vertically between sequences (Oliver., 1971; Ambrose et al., 2009; Hentz et al., 2014). Many Woodbine fields produce from a combination of structural and stratigraphic traps associated with salt mobilization (Wood and Giles, 1982; Jackson and Seni, 1984). The remaining petroleum in the East Texas reservoir is estimated by Wang et al., 2008 to be approximately 1.58 BSTB However, much of this remaining potential is limited because of reservoir compartmentalization, a function of facies complexity (Ambrose et al., 2009). This recent estimate has created interest in the Woodbine sandstones in the other parts of the East Texas Basin, especially in the eastern part of the East Texas Basin. The eastern part of the East Texas Basin served as migration routes of the Upper Cretaceous oil to East Texas Field, which are from the Harris Sands in the southern part of the East Texas through the Neches oil field and along the erosional pinch-out in the eastern part of the East Texas Basin (Wescott and Hood, 1994). The Harris Sandstone termed by oil and gas operators is a product of the Woodbine erosion during rose of the Sabine Uplift in the Cenomanian (Oliver, 1971), resulting in an interception of the Harris sands and hydrocarbon generated from the Eagleford and Rapides shales (Wescott and Hood, 1994). In addition to migration pathways of the East Texas Basin, a low-relief anticlinorium structure combined with the heterogeneous deposits serve as a hydrocarbon traps in Neches oil field (Champion, 1954; Fisher and Galloway, 1983).

Although there is high well density and a long history of Woodbine production in East Texas field and other fields such as Kurten and Hawkins in the East Texas Basin (Galloway et al., 1983), research into the sequence stratigraphy and depositional systems of the Woodbine Group at other areas in the East Texas Basin remains to be carried out. There is still an absence of comprehensive studies in the eastern and southeastern parts of the East Texas Basin. Accordingly, this study focuses on the Woodbine Group in Anderson and Cherokee Counties.

Based on integration of core and wireline log analyses, this study aims to (1) characterize lithology and facies-distribution within the study area; (2) identify the chronostratigraphic framework of the Woodbine Group within the study area by applying sequence stratigraphic analysis; and (3) interpret depositional systems and trends of potential reservoir sandstones by generating gross-sandstone maps of the Woodbine Group in Anderson and Cherokee Counties.

STUDY AREA

The study encompasses approximately 3,085 km^2, encompassing Anderson and Cherokee Counties in the southeastern part of the East Texas Basin (Figure 1.1). The database in this study consists of 1,003 raster well logs, distributed throughout the study area and slabbed core from one well in the northeastern of Cherokee County. The study area was selected because (1) there are a few comprehensive studies on depositional systems in this area; and no gross-sandstone maps of the Woodbine Group have previously been made for Anderson and Cherokee Counties, even though these deposits are potential reservoirs (Ambrose et al., 2009).

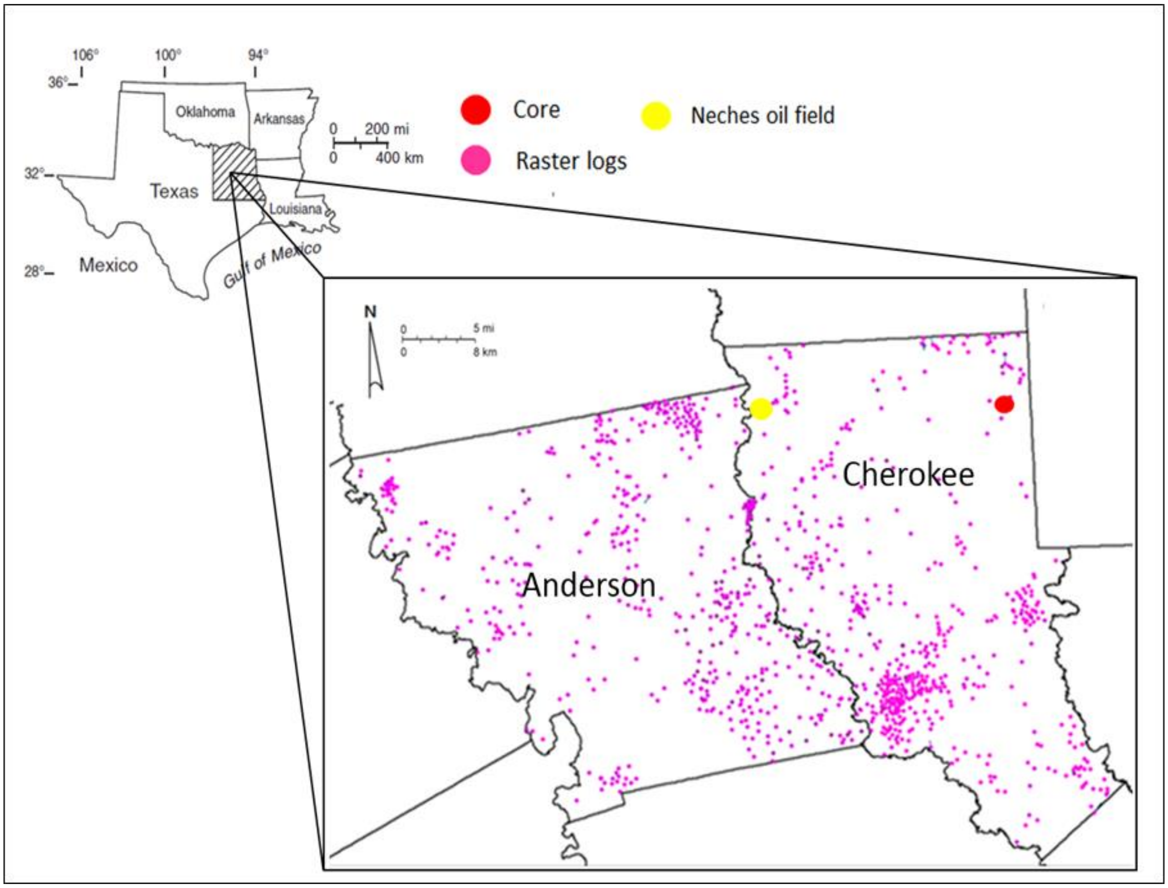

Figure 1.1: Study area encompasses approximately 3,085 km^2, including Anderson and Cherokee Counties.

REGIONAL GEOLOGICAL SETTING

The East Texas Basin is bounded on the west and north by the peripheral graben of the Mexia-Talco fault system (Ewing, 1991a, b). The East Texas Basin was formed as a pull-apart rhombic basin during the Mesozoic period (Jackson and Seni, 1984). The formation of the East Texas Basin was controlled by a board rift complex of Late

Triassic-Early Jurassic age that generated differential subsidence. After the subsidence events had been disturbed by Late Mesozoic Uplifts and related igneous activity, only minor Cenozoic reactivation of structures, gentle uplift, and tilting occurred within the basin (Ewing, 1991a). From the Early Cretaceous to the earliest Late Cretaceous, the basin was marine and followed by a widespread marine limestone unit, known as Buda Formation. In the mid-Cenomanian, the major relative sea-level fall in response to the uplift at the southern part of the Mississippi embayment exposed the shallow shelves and platforms around the flanks of the basin, resulting in a widespread unconformity. However, the central part of the present East Texas Basin remained covered by the sea, leading to continuous deposition from the Cenomanian to the Turonian. Accordingly, the Buda Formation is overlain by the conformable Maness Shale, overlain by the Woodbine Group (Salvador, 1991). The Early Cretaceous sediments interacted with salt diapirs, which were initiated during Late Jurassic age. During this time, the East Texas Basin had substantial bathymetric expression, resulting in the deposition of the Tertiary strata (Ewing, 1991a, b).

During the Late Mesozoic, structural deformation of the East Texas Basin includes fault zones and salt mobilization (Figure 1.2). Today the East Texas Basin is bordered by major structural elements, consisting of the Ouachita Mountains, Sabine Uplift, Mount Enterprise fault zone, Angelina-Caldwell Flexure, Mexia-Talco fault zone, and salt domes (Jackson, 1982). The Ouachita Mountains, located on the north side of the East Texas Basin, was a main source of Woodbine sediment (Halbouty and Halbouty, 1982). The Sabine Uplift is a low-relief, broad pear-shaped anticlinorium, lying astride the Texas-Louisiana border between the East Texas and North Louisiana diaper provinces (Ewing, 1991a). Halbouty and Halbouty (1982) proposed two short-term episodes of the active Sabine Uplift. The first episode began just after Buda deposition in the Early Cretaceous, resulting in an erosion of up to 2,500 m of Lower Cretaceous strata at about 100 Ma (Ewing, 1991b). After being covered with Woodbine or Tuscaloosa deltaic strata, the second episode occurred during the deposition of the Upper Woodbine Group and Eagle Ford Group, resulting in erosion of several hundred meters of Woodbine and earlier strata at about 90 Ma before the unconformable deposition of Austin Chalk (Halbouty and Halbouty, 1982; Ewing, 1991b). Ewing (1991b) expanded to include the final episode of uplift occurred in the Eocene period, resulting in the present outcrops. In Tertiary age, sediment loading in the Gulf of Mexico basin to the south caused down flexure along the southern margin of the Sabine Uplift, known as Angelina-Caldwell Flexure.

In contrast, Ambrose et al. (2009) demonstrated that the Sabine Uplift was a continuous process, gradually developing during the period of Woodbine and Eagle Ford deposition because the stratigraphic framework of the basin records a steady rate of subsidence. Moreover, the Woodbine deposits were directly overlain by impermeable Austin Chalk as seal of reservoir because the uplift caused erosion on Woodbine and Eagle Ford Groups, resulting in eastward thinning and tilting of strata (Stehli et al., 1972; Ambrose et al., 2009). At the south-central margin, the basin is bordered by the Mount Enterprise fault zone and Angelina-Caldwell Flexure (Jackson, 1982). The Mount Enterprise fault zone is a belt of normal faults with east-west trend on the southern and southeastern border of the East Texas Basin, extending eastward onto the Sabine Uplift. The fault zone consists of down-to-the north normal faults of listric, straight faults and associated antithetic faults, causing movements in the Late Jurassic and Early Cretaceous (Stehli et al., 1972; Ewing, 1991b). In contrast, the Angelina-Caldwell Flexure is a monoclinal-hinge line, representing the continental shelf edge in the Late Cretaceous (Stehli et al., 1972). However, Hentz et al., (2014) claim that the Edward Reef Trend marks the Woodbine shelf edge. The western margin is bordered by the Mexia-Talco fault zone, a pull-apart structure associated with salt mobilization that allowed overburden creep into the East Texas Basin (Jackson, 1982). The central part of the basin consists of numerous salt domes such as Boggy Creek salt dome at Anderson and Cherokee Counties (Mclellan et al., 1932; Jackson, 1982). The salt mobilization and rapid influx of sediments from the Ouachita system caused Cretaceous subsidence, coinciding with Woodbine deposition (Ambrose et al., 2009). Accordingly, more accommodation space could be countered with the eustatic fall, resulting in preservation of Woodbine incised-valley fills (Ambrose et al., 2009; Hentz et al., 2014).

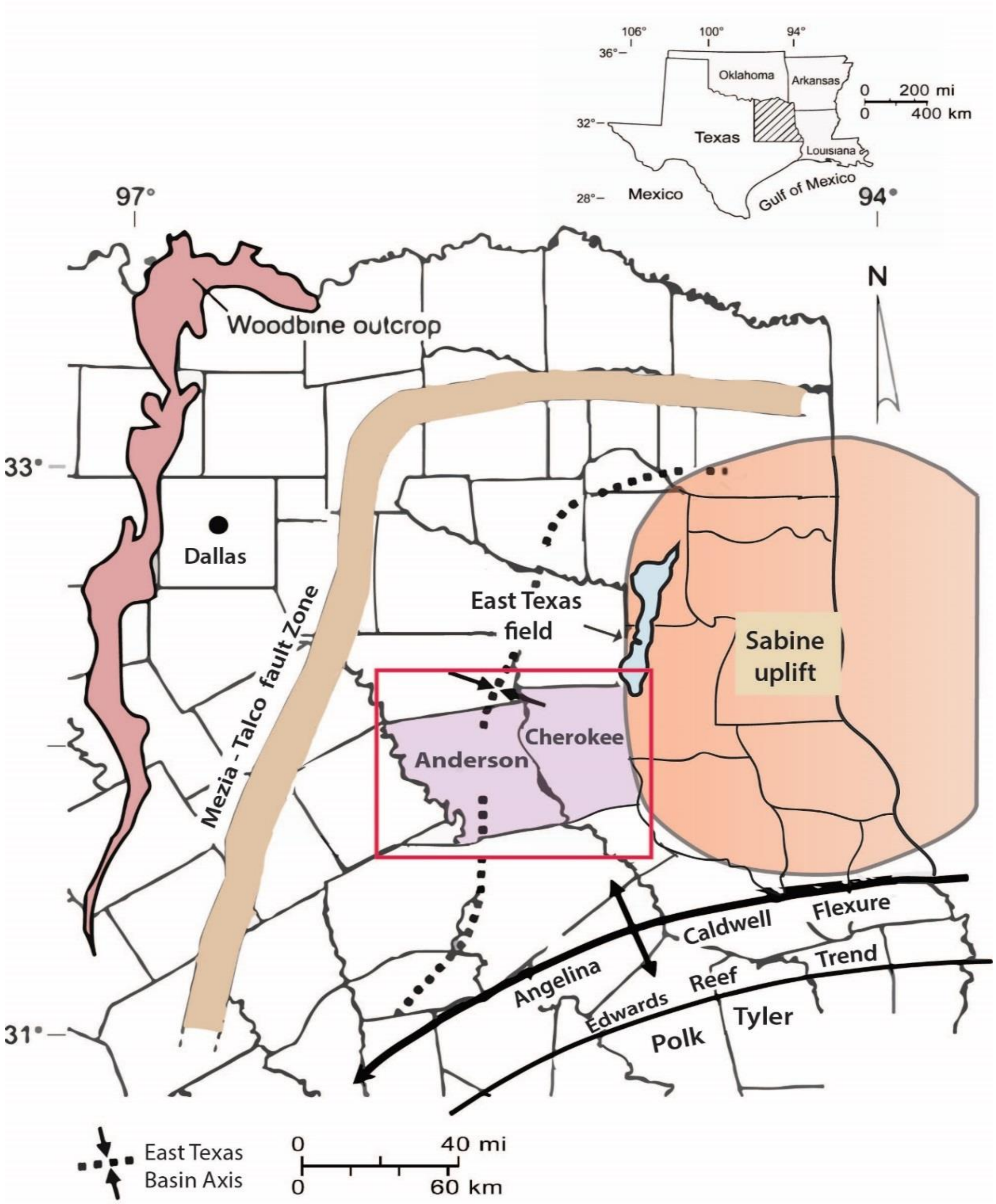

Figure 1.2: The geological feature map of the East Texas Basin described by Siemers (1978) (modified from Ambrose et al., 2009)

REGIONAL STRATIGRAPHY

The East Texas Basin contains sediments from Late Jurassic through Eocene that are approximately 22,000 ft thick (Halbouty, 1991). The Woodbine Group is siliciclastic succession between the Washita Group at the base and the Eagle Ford Group at the top (Figure 1.3). In the eastern part of the basin, the Woodbine Group is directly overlain by the Austin Chalk and is eroded by the Base-of-Austin-Chalk unconformity (Halbouty and Halbouty, 1982; Ambrose et al., 2009). Like in the eastern part, the Woodbine deposits in the southwestern part of the East Texas Basin represent several pinch outs of fourth-order sequences onto the Eagle Ford Group (Hentz et al., 2014).

The Washita Group consists of Buda Limestone Formation and Maness Shale. According to Haq et al., 1998, the highstand system tract of the Buda limestone is overlain by a regional unconformity, indicating a third-order sequence (94 million years (Ma.). This regional unconformity is conformably overlain by a third-order transgressive system tract of the Maness Shale, in turn overlain by a maximum flooding surface, dated at 93.5 Ma (Haq et al., 1998). The subsequent Woodbine succession was deposited as a third-order regressive system tract during the Middle and Late Cenomanian (Ambrose et al., 2009). A maximum of 14 fourth-order sequences in the Woodbine Group are preserved along the basin axis. Fewer cycles occur westward toward the Mexia-Talco fault zone and eastward toward the Sabine Uplift, where the Woodbine Group is truncated by the Base-of-Austin-Chalk unconformity (Ambrose et al., 2009; Hentz et al., 2014)

Oliver (1971) proposed that the Woodbine Group is composed of two regressive formations; the Dexter Formation (lower Woodbine) and the Lewisville formation (upper Woodbine), which are informal stratigraphic terms used by oil and gas operators. The

Dexter Formation consists of sand-rich deposits from a fluvial system in northeast that merges into a deltaic system to the south in the East Texas Basin. Meanderbelt sand bodies are constrained by the coeval flood plain deposits. The Lewisville Formation represents a mud-rich, retrogradational system composed of muddy shelf and strandplain deposits. However, Ambrose et al. (2009) proposed that thick individual sandstone bodies (commonly >100-ft) in the Dexter Formation represent bedload fluvial channel-fill deposits within incised valleys that formed during periods of base-level fall.

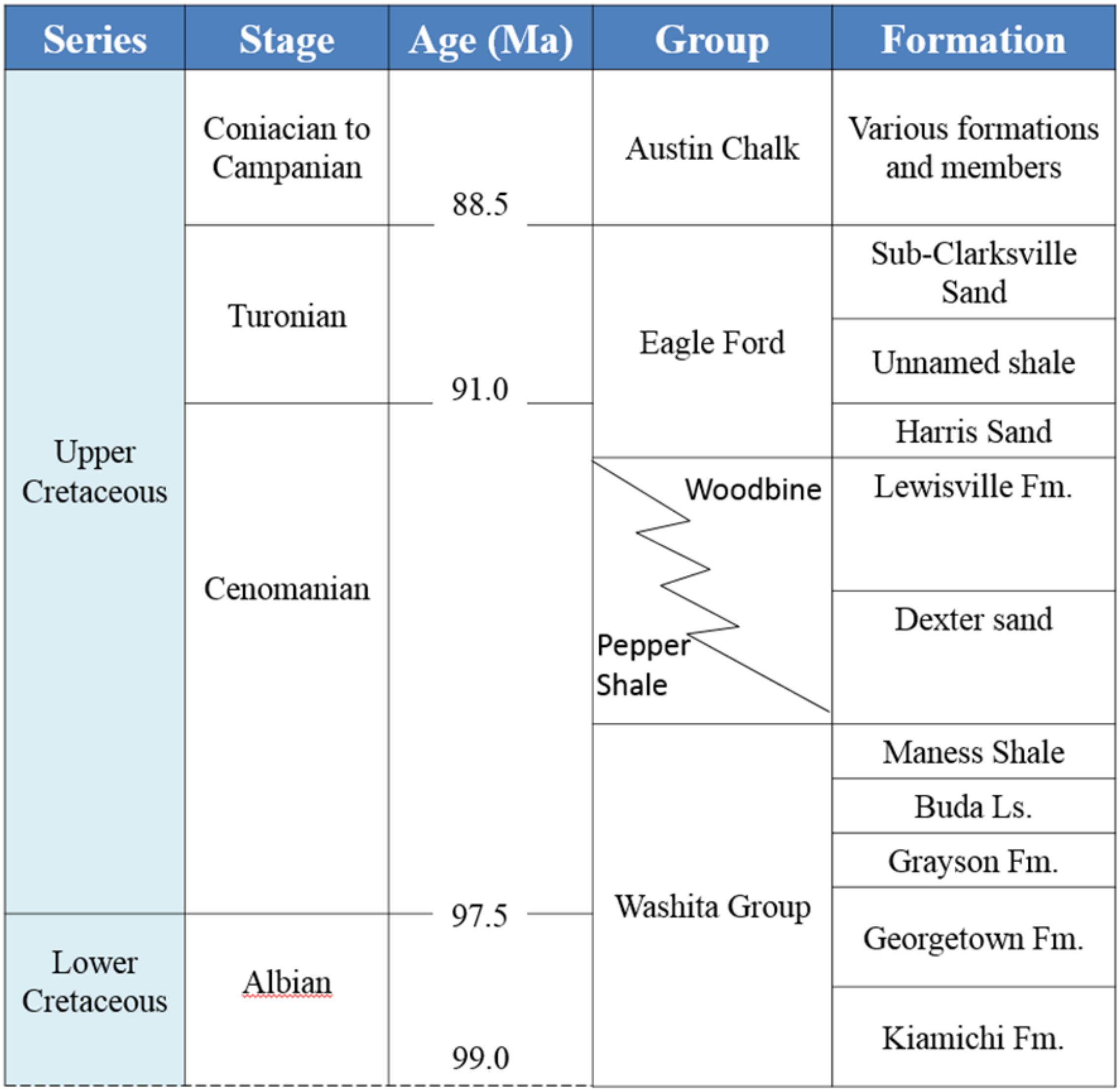

Figure 1.3: Chronostratigraphy and lithostratigraphy of the East Texas Basin, ranging from the lower to upper Cretaceous (Ambrose et al., 2009).

PREVIOUS STUDIES

East Texas oil field, discovered in 1930, is the largest conventional oil field in the Lower 48 States in terms of OOIP. The main producing stratigraphic unit in East Texas oil field is the Cenomanian -Woodbine Group (Minor and Hanna, 1941). The Woodbine Group has been the subject of numerous studies. Adkins (1932) described the lithostratigraphy, followed by regional lithofacies and depositional systems mapping by Oliver (1971).

The East Texas Basin is bordered in north and west by the Mexia-Talco fault system. Sedimentation of the East Texas Basin records intermittent, syndepositional salt mobilization that locally controlled subsidence and accommodation space. The Woodbine Group, consisting of the older Dexter and younger Lewisville Formation is thinner westward to the Mexia-Talco fault zone and eastward to the Sabine Uplift (Ambrose et al., 2009).

Oliver (1971) reported more details of the regional depositional framework of the Woodbine Group based on the integration of outcrop observations and wireline-logs. Woodbine sediments were deposited in three major depositional systems, consisting of fluvial, high-destructive deltaic, and shelf-strandplain systems (Figure 1.4). Oliver (1971) concluded that the Lower Woodbine succession was composed of a fluvial system that graded southward into coeval system of distributary-channel, lower-delta-plain, and coastal-barrier facies. Upper Woodbine successions were dominated by a deltaic and shelf-strandplain systems that record a net-retrogradational system. In the eastern part of the basin, the Woodbine succession was eroded toward the west flank of the Sabine and subsequently redeposited southward as the Harris sand, an informal paleogeographic term used by oil and gas operators.

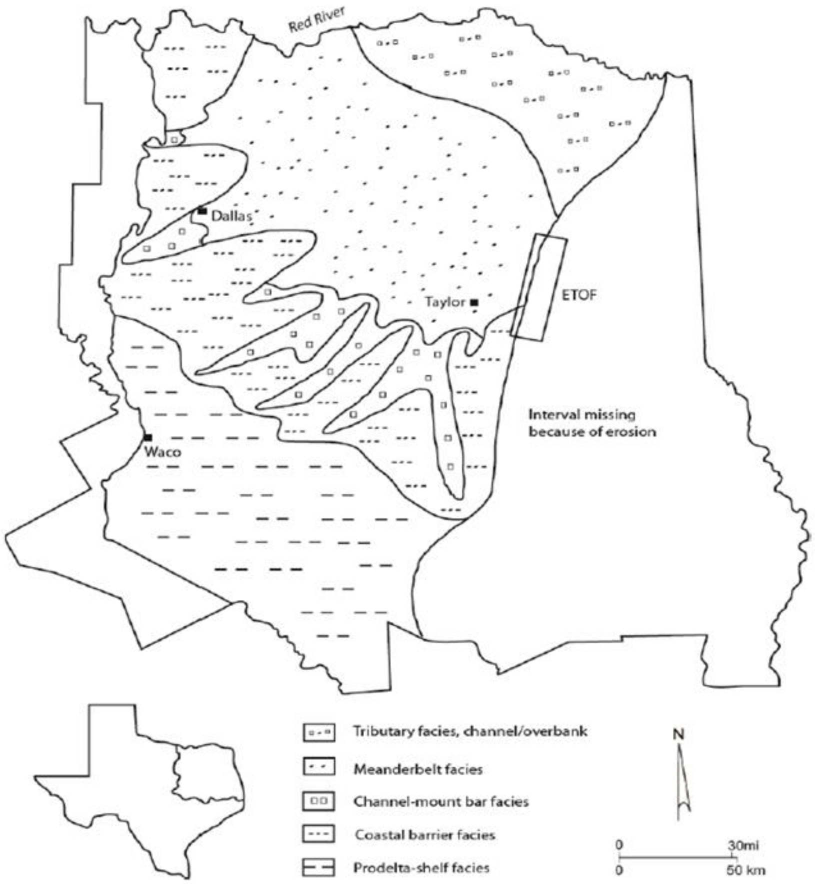

Figure 1.4: Regional depositional systems in the Woodbine Group in the East Texas Basin (Oliver, 1971)

Fisher and Galloway (1983) described the potential for additional oil recovery in the Woodbine Group in Neches oil field, in the eastern part of the East Texas Basin shown in Figure 1.1. They stated that Neches field is dominated by meanderbelt systems, consisting of channel-fill, point-bar, floodplain, and levee facies. Meanderbelt-channel systems in Neches field are recognized by upward-fining textural trends that record lateral accretion, resulting in an upward decrease in permeability, as well as permeability stratification with an arcuate shape in plan view. Point-bar complexes in Neches field developed as a stacked series of laterally offset sandstone bodies, separated by muddier deposits of continuous floodplain mudstone beds. These point-bar complexes produce oil within anticlinal traps (Figure 1.5). Moreover, truncation of floodplain deposits and clay plugs in abandoned-channel fill facies are inferred to have formed barriers to fluid flow, controlling vertical heterogeneity and compartmentalization of reservoir units.

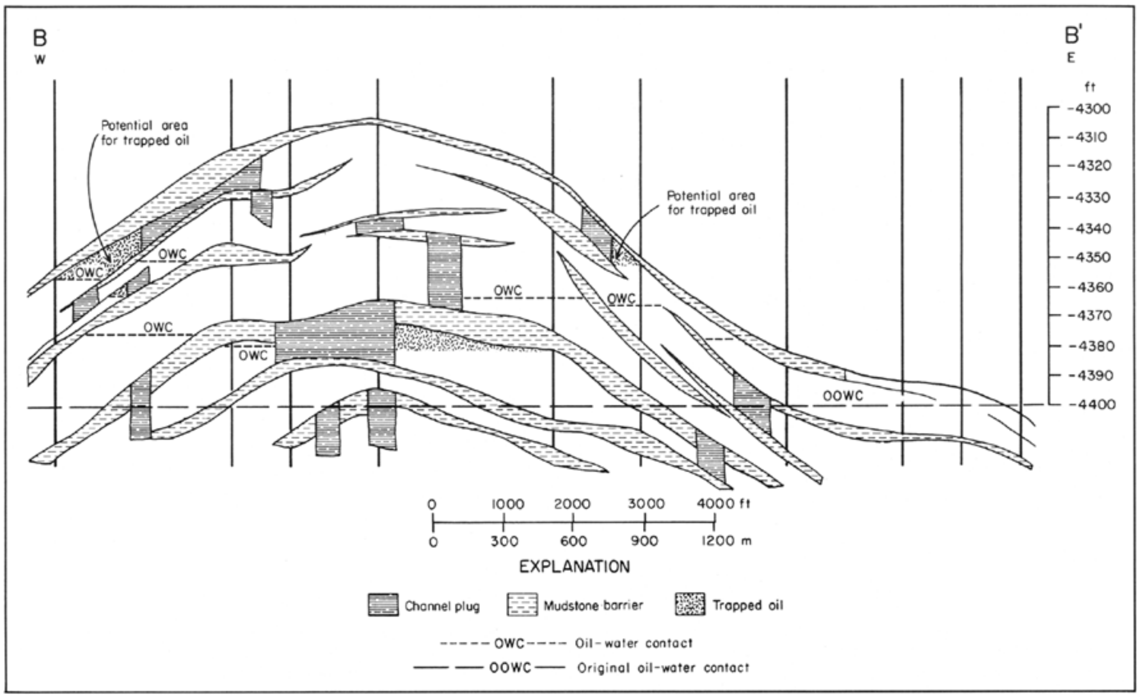

Figure 1.5: Cross section of anticlinal trap in Woodbine reservoirs in Neches field with stacked sandstone bodies composed of meanderbelt channel-fill facies from information in hearings files of the Railroad Commission of Texas, modified by Fisher and Galloway (1983).

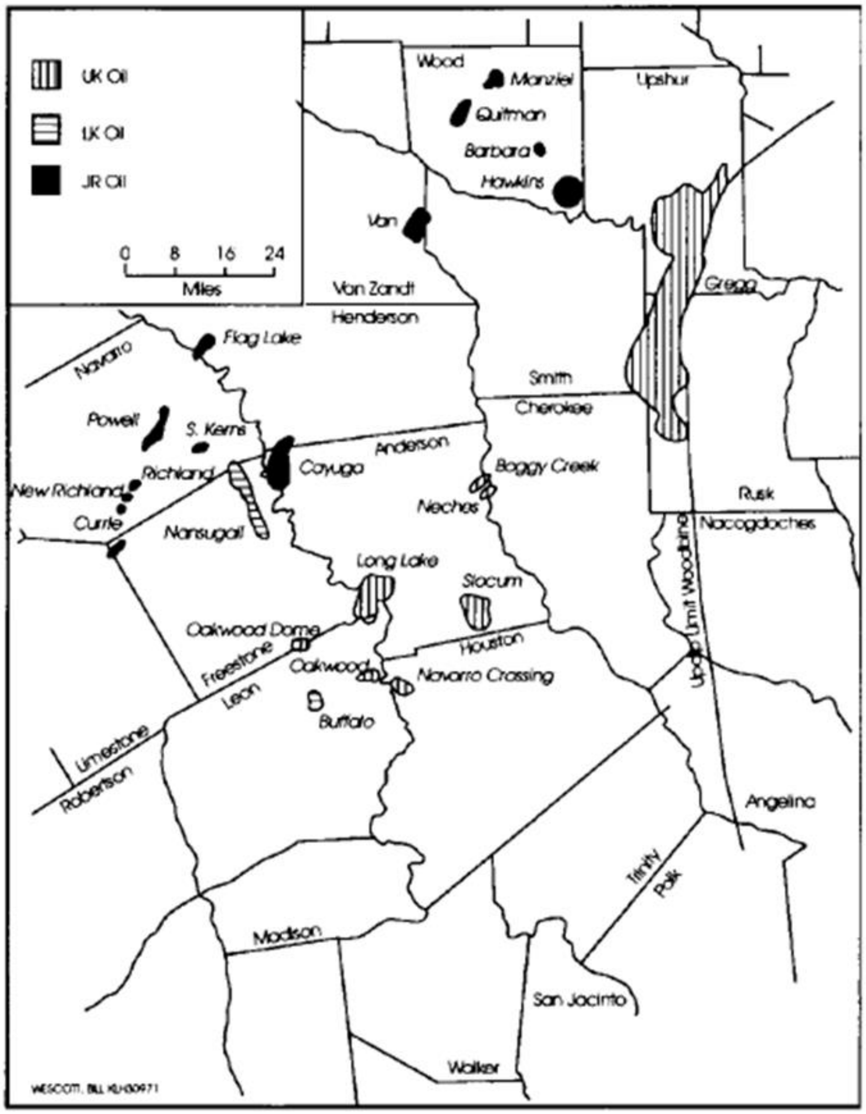

Figure 1.6: Migration pathway of Upper Cretaceous oil in the Woodbine Group from Wescott and Hood (1994).

In contrast to previous studies based on the outcrop observations and sparse wireline-logs, Ambrose et al. (2009) used a sequence-stratigraphic approach in characterizing the Woodbine Group, integrating core and log data from closely spaced wells in East Texas field and adjacent areas. Ambrose et al. (2009) demonstrated that the third-order transgressive system tract and its associated maximum flooding surface (MFS 10) of the Maness Shale is dated at approximately 93.5 Ma and termination of the Woodbine deposition is at approximately 92 Ma (Haq et al., 1988), supported by micropaleontologic studies of the Maness Shale by Loeblich and Tappan (1961). Accordingly, Ambrose et al. (2009) proposed that the Woodbine Group is composed of a single third-order sequence, representing a period of 1.5 m.y. sand fourth-order deposits, each representing 110 k.y. The deposits of the fourth-order sequences of the Woodbine succession were interpreted as a series of sandy, lowstand valley-fill sequences that eroded relatively muddier highstand deltaic deposits. Previous studies (Oliver, 1971; Fisher and Galloway, 1983) stated that blocky gamma-ray responses represented channel-fill deposits within a mixed load, meanderbelt system flanked laterally by coeval floodplain facies. These meandering sandstone bodies were interpreted to have merged southward with barrier-strandplain and wave-dominated deltaic sandstone bodies. In contrast, Ambrose et al. (2009) interpret these blocky gamma-ray responses as indicating regionally continuous, basin-scale incised-valley river systems deposited during episodes of relative base-level fall, cutting into older fluvial-dominated deltaic facies of highstand system tracts. Thus, they document no genetic connection between these incised valleys fluvial and relatively older deltaic systems. Complexity in the Woodbine highstand systems tract is dominated by sandy, discontinuous distributary channel sandstones, pinching out into muddy delta-plain and distributary-bay facies.

Similar to those described by Ambrose et al. (2009), Hentz et al. (2014) proposed that the number of fourth-order sequences of the Woodbine succession decrease westward to the outcrop belt and eastward to the Sabine Uplift in the southwestern part of the East Texas Basin. This decrease causes an unconformable contact between the Eagle

Ford Group and the Woodbine Group in the East Texas Basin, consisting of multiple depositional pinch outs. Rather than constituting a regional unconformity, the upper Woodbine section contains several pinch-outs toward the Eagle Ford Group as apparent truncation, a term described by Vail (1987). This apparent truncation records depositional pinch-outs that represent parallel seismic reflectors within a low-order transgressive system tract.

Ambrose et al. (2012) asserted that incised-valleys transported sediments to the Woodbine shelf-edge located in Polk County during sea-level fall, forming the Woodbine shelf-edge deltaic system that are characterized by thick distal delta front successions, consisting of turbidites and fine-grained sediments over muddy siltstones graded upward into sandy proximal delta and channel mouth-bar facies with planar-stratifications. The Woodbine shelf-edge delta fed some deposits to a deep-water system through slope failure, resulting in debris-flow, slump deposits, and turbidites. Ambrose et al. (2014) proposed that the Woodbine deposits in northwestern Tyler County represent slope setting, defined by sparsely burrows mudstones with thin fine-grained sandstones. Moreover, the sandier Woodbine sediments were identified as debris flow and channelized levee facies in a deep-water environment similar to lower Tuscaloosa Formation in the south-central Louisiana, described by Woolf (2012).

In order to optimize production recovery, the petroleum system, including a source rock, migration, reservoir, seal, and trap should be well understood (Wescott and Hood, 1994). According to the study by Halbouty and Halbouty (1982), the Sabine Uplift played an important role in reservoir systems of the eastern part of the East Texas Basin. Because of the higher elevation of the Sabine Uplift, hydrocarbons migrated toward the eastern basin. However, Wescott and Hood (1994) proposed that upper Cretaceous oil migrated up to the steepest dip through two flow lines, converged at the East Texas field. First, upper Cretaceous oil migrated updip from the Harris sands, located in Houston, Madison, Grimes, and Walker Counties to the East Texas field. During the active of Sabine Uplift in the Cenomanian, the Harris sands deposited as sand lobes, which are intercept with hydrocarbon generated from the Eagle Ford Group and/or Rapides shales to the south and serves as an updip migration pathway of oil. Another flow line passes through Neches field in northwest Anderson and northeastern Cherokee Counties as shown in Figure 1.6.

The Woodbine succession has an average permeability of 600 millidarcys and 26% average porosity. Woodbine reservoirs occur within a northeast-southwest trend of a low-relief anticlinal structure with minor faulting (Cawthon and Slater, 1964). The low-relief anticlinal structure was formed by deep-seated salt masses as shown in Figure 1.7 and 1.8 (Wood and Giles, 1982; Galloway et al., 1983). Although remaining oil in East Texas field is estimated at 1.58 BSTB, only 70 MMSTB will be produced with existing wells and current waterflood operations (Wang et al., 2008). Poorly swept Woodbine reservoirs occur in heterogeneous lower Woodbine highstand deltaic stringers which can be more effectively produced with strategically targeted, deepened wells and redesigned waterfloods. Blocky gamma ray log responses in the Dexter Formation are interpreted as incised-valley deposits, whereas laterally adjacent mudstone sections with serrate log responses are interpreted as relatively older highstand deltaic deposits (Ambrose et al., 2009). Moreover, Wang et al. (2008) suggested that these stringers should be operated separately from the Main Woodbine sandstones with small-scale, areally limited waterfloods. According to sandstone-poor areas, the recovery efficiency of the East

Texas field can be optimized by reducing the number of water injection wells in the unproductive area such as muddy delta front facies (Ambrose et al., 2009).

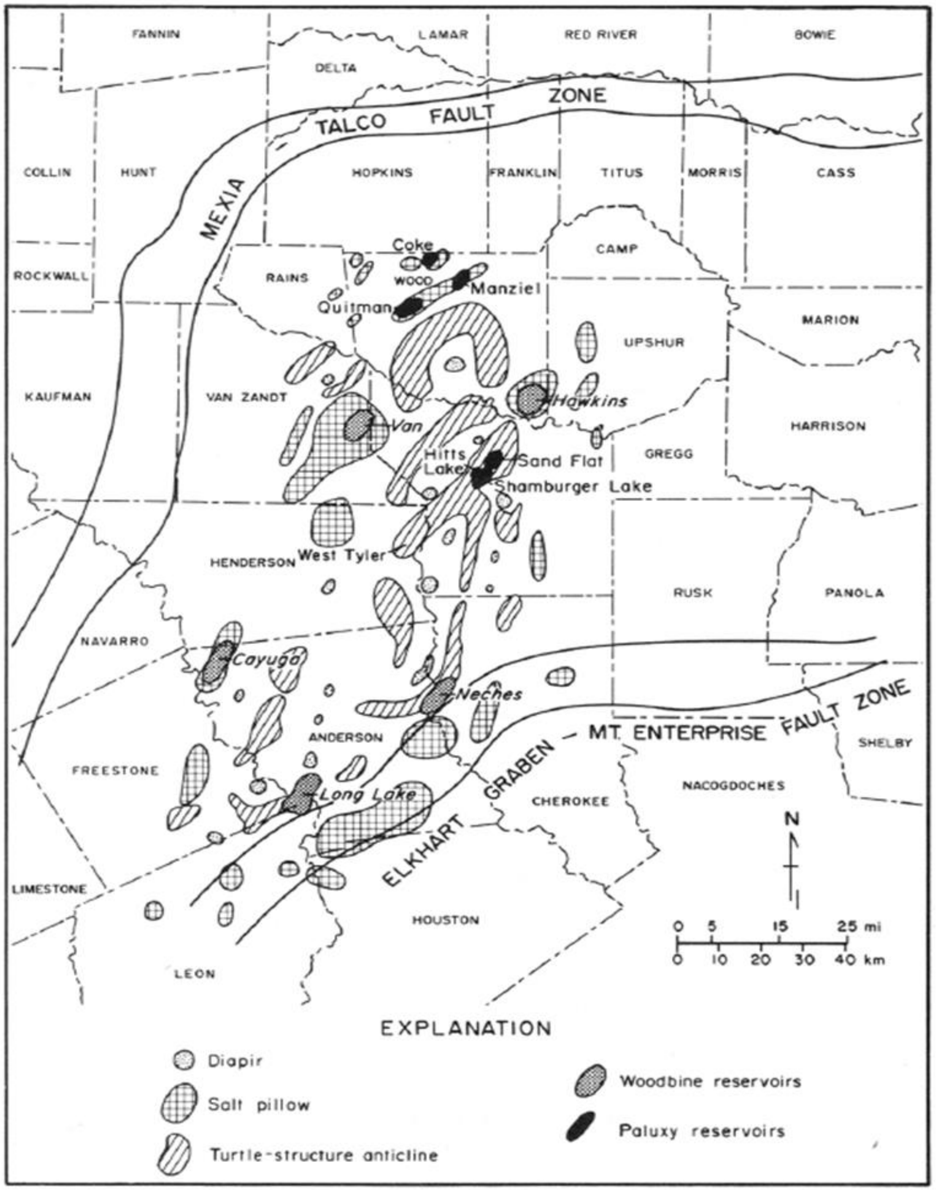

Figure 1.7: Distribution of Cretaceous clastic reservoirs and turtle-structure anticlines, associated with salt anticlines and salt diapirs in the East Texas Basin. From Galloway et al. (1983).

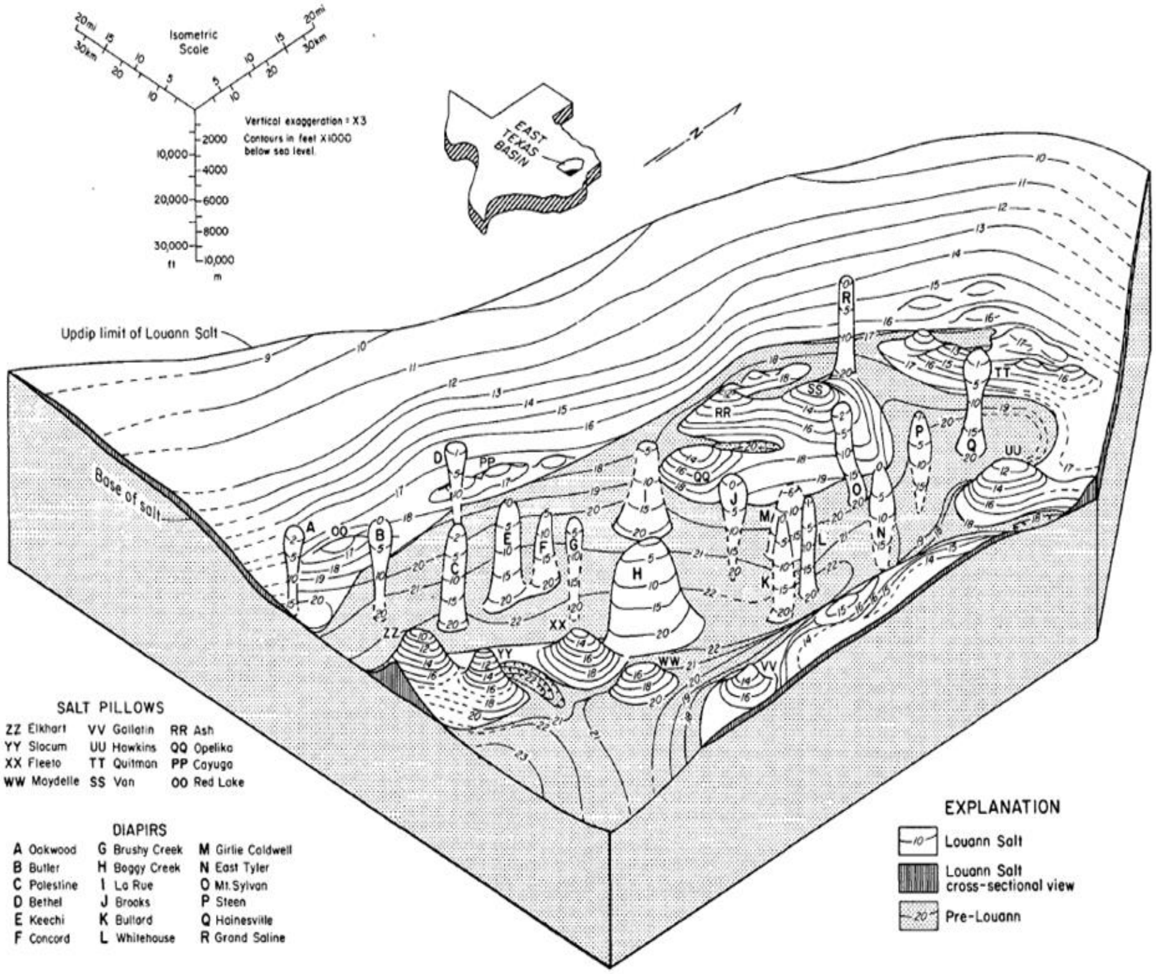

Figure 1.8: Isometric block diagram, showing the configuration of salt structures in the East Texas Basin from Jackson and Seni (1984).

Chapter 2: Objectives, Database and Methods

The objectives of this study are to (1) characterize lithology of the Woodbine Group in a 3,085 km^2 area in the eastern part of the East Texas Basin, encompassing Anderson and Cherokee Counties; (2) establish a chronostratigraphic framework of the Woodbine Group within the study area by applying sequence stratigraphic analysis; and (3) define gross sandstone thickness in selected depositional intervals of highstand and lowstand origin, and (4) infer depositional systems and trends of potential reservoir sandstones of the Woodbine Group.

More than 1,000 wells have been drilled in Anderson and Cherokee Counties. Few new wells have been drilled since 1990 (Ambrose et al., 2009). According to Galloway et al. (1983), the Woodbine deposits of the Neches oil field, located at the northeastern Anderson and northwestern Cherokee Counties (Figure 1.1) have 25% of porosity and 1020 md of permeability. Even though the East Texas Basin has a long production history with numerous wells, most wells penetrate only the upper part of the Woodbine succession, the main productive section (Halbouty, 1991). Most production occurred in the upper section of the Woodbine Group, known as the Main sand, because sandstone-body architecture is more consistent with high permeability. However, the Lower Woodbine Group, called stringer sandstones have high degree of discontinuity, resulting in lower connectivity (Galloway et al., 1983). Thus, the analysis of this study are only restricted to wells that penetrate the entire Woodbine section in order to access the remaining petroleum.

The study area encompasses 3,085 km^2, encompassing Anderson and Cherokee Counties in the eastern part of the East Texas Basin. The database in this study consists of about 1,000 raster well logs and a 202-ft slabbed core from one well in northeastern Cherokee County, operated by the American Petroleum Cooperation. The core samples are used for lithology characterization and depositional systems interpretation. The stratigraphic correlation and identification of net-sandstones are primarily based on the gamma-ray logs (GR-log), spontaneous potential logs (SP-log), and resistivity logs. GR-logs are used to identify and characterize lithology and to infer vertical grain-size trends, because thin beds are better resolved by the GR curve. However, many wireline logs in the study area do not have GR curves. Although SP logs can be used to identify lithology and potentially porous zones, it cannot be used to resolve thin beds. Resistivity logs are mainly used for fluid estimation within formations, but this study does not include fluid identification. Therefore, the objective of resistivity logs in this study is to differentiate limestone from sandstone beds.

To interpret sequence stratigraphy from wireline logs, this study followed the method of Van Wagoner et al. (1990) and Mitchum et al. (1993). Based on SP and GR logs, the fourth-order stratigraphic framework was established by defining stratigraphic surfaces, including sequence boundary (SB), transgressive surface (TS), and maximum flooding surface (MFS). Correlated surfaces are indicated with consecutive number, starting at 10 and increasing by 10 for each successive sequence (For example, MFS 10, MFS 20,…, MFS 100, nomenclature adopted from Ambrose et al. (2009). Third-order stratigraphic surfaces encompassing the Woodbine Group were initially recognized before being comprehensively applied throughout the entire Woodbine succession. The top of the Buda Limestone was defined as SB 10, represented by consistently low GR values and extremely high resistivity values. The overlying Maness Shale was divided into two units: (1) upward-fining (retrogradational) unit and (2) upward-coarsening (progradational) unit, separated by a third-order maximum flooding surface (MFS 10). The top surface of the studied interval is located above the transgressive system tract in the lowest part of Eagle Ford Group. By matching pattern, a sequence boundary (SB) was placed at the base of an incised-valley fill of a lowstand system tract, correlated with the top of a younger highstand system tract. According to Van Wagoner and Mitchum (1990), incised-valley fills are characterized by thick, blocky and blocky to upward-fining SP-log responses with erosion base (SB), truncating the underlying highstand deposits. In contrast, a highstand system tract is defined by an overall upward-coarsening to serrate SP-log profile. A transgressive surface (TS) occurs at the top of an incised-valley fill and the top of a younger highstand system tract, recognized by the diagnostic upward-fining pattern on SP-log responses. The top of a regional upward-fining pattern was identified as a maximum flooding surface (MFS). Unlike a discontinuous upward-fining pattern of abandoned channels, the top of regional upward-fining SP-log responses (MFS) represents an extensive condensed section which is formed when the shoreline reaches maximum landward migration (Catuneau, 2006).

To calculate gross-sandstone values for each zone mapped in this study, SP logs were calibrated to gross-sandstone values from core. Accordingly, this study consistently applied the one-third (33%) of distance from the maximum shale line to the maximum sandstone line as a cut-off line on both GR and SP-log responses. Gross-sandstone maps of a lowstand and highstand systems tract within each sequence were initially constructed by Petra software and re-contoured by hand to eliminate areas of tightly spaced and anomalous contours introduced by suspect data values or by limitations in contouring algorithms (edge-projection effects and geologically unrealistic patterns). To support interpretation from wireline logs, lithology and facies distributions were integrated with interpretations from core data.

The main limitations of this study are the quality of old wireline log data and limited core samples. Moreover, many wireline logs in the central and southeastern part of the study area do not penetrate the lower Woodbine succession. As a result of all these data limitations, the stratigraphic framework was primarily based on SP logs, with consequent lack of resolution of some thin beds. Furthermore, the core analysis is based on slabbed core from only one well in the northeastern part of the study area near the Sabine Uplift. Thus, the slabbed core does not completely represent the Woodbine succession that becomes thinner eastward toward the Sabine Uplift (Ambrose et al., 2009; Hentz et al., 2014).

Chapter 3: Sequence stratigraphy

Sequence stratigraphy is the study of rock relationships within a genetically related chronostratigraphic framework (Van Wagoner and Mitchum, 1990; Catuneau, 2006). A Sequence is defined as a fundamental strata unit, forming a characteristic stacking pattern in response to the interplay of accommodation and sedimentation as a result of fluctuation of sea level, tectonic activities, the volume of sediments, and climate changes (Vail and Wornardt, 1991).

The stratigraphic analysis in this study is based on the genetic stratigraphic sequence (Galloway, 1989). Galloway (1989) proposed that the genetic stratigraphic sequence consists of lowstand, transgressive, and highstand system tracts, bounded by maximum flooding surfaces. Galloway (1989) claimed that maximum flooding surfaces are better for regional stratigraphic correlation than the other surfaces for the following reasons. The maximum flooding surface is a single and regionally extensive shale unit, bounded the genetic sequence of both continental and marine by the same surface. Accordingly, maximum flooding surfaces are easy identified and correlated on well logs across a basin. Moreover, the maximum flooding surface is a condensed section with a pelagic marker, which can be extrapolated into nonmarine and deep marine section. Furthermore, the genetic sequence can overcome many problems associated with depositional sequence –bounded by subaerial unconformity and its marine correlative conformity. For example, Holbrook and Bhattacharya (2012) claimed that a subaerial unconformity (SU), which is used as a sequence boundary in depositional sequence is not abruptly formed as a synchronously topographic exposure surface of sediment bypass by deep incision of valleys during sea-level fall as described by Van Wagoner et al. (1988).

According to flume observation and field data, Holbrook and Bhattacharya (2012) stated that the SU is a time-transgressive surface and never fully exposed along its length because incised-valleys are incised, locally reshaped, and covered by fluvial sediments simultaneously as it is scoured throughout the regressive/transgressive cycle. Therefore, SU records cumulative scours instead of instantaneous topographic surface, binding lower-order erosional surfaces within valley fills. In addition, the SU is not only controlled by eustatic fall as MFS but also by sediment supply, resulting in marine sediment starvation when significant sediments stored within fluvial strata above RCS (Galloway, 1989). RCS surfaces can also be formed by tectonic, climate change, and other process (Holbrook and Bhattacharya, 2012).

SYSTEM TRACTS

Sequences can be subdivided into system tracts, which are defined by Brown and Fisher (1977) as a linkage of contemporaneous depositional system based on stacking patterns, position within the sequences, facies association, and types of bounding surfaces, including a maximum flooding surface (MFS), transgressive surface (TS), and sequence boundary (SB) (Catuneanu, 2006). Each system tract represents a specific type of stratal stacking pattern associated with potential hydrocarbon reservoirs, required different exploration principles (Vail and Wornardt, 1991). Furthermore, in order to interpret lateral facies relationships, the analysis must be done separately for each conformable sequence, because there is no genetic linkage between facies above and below the bounding surface (Van Wagoner and Mitchum, 1990).

Highstand system tract

The highstand system tract forms during the late stage of relative sea-level (RSL) rise, when the rate of sedimentation exceeds the rate of sea-level rise. The boundaries of the highstand system tract are the maximum flooding surface at the base and sequence boundary at the top. As shown in Figure 3.1, the highstand system tract is commonly dominated by aggradational stacking pattern in the early stage and progradational stacking pattern in the late stage of highstand (Catuneanu, 2006). Highstand deposits typically consist of fluvial, coastal, and shoreface deposits near the basin margin as a result of high accommodation created by sea-level rise. The highstand wedge develops the steeper slope gradient of delta front environments than the fluvial profile, leading to preferential fluvial incision during subsequent sea-level fall.

Lowstand system tract

The lowstand systems tract forms during the falling and lowstand phase of the sea-level cycle (Holbrook and Bhattacharya, 2012). The lowstand system tract is bounded by subaerial unconformity and its marine correlative conformity at the base and by maximum regressive surface at the top (Catuneanu, 2006). The Woodbine Group within the East Texas Basin deposited in continental shelf environments such as fluvial to coastal systems and shallow-marine systems (Oliver, 1971; Fisher and Galloway, 1983; Ambrose et al., 2009; Hentz et al., 2014). However, under similar tectonic conditions, high sedimentation rates, the lower Tuscaloosa Formation at the east side of the Sabine Uplift, equivalent to the Woodbine Group, represents shelf-edge deltaic to basin floor fan systems and a preservation of incised-valley fills (Woolf, 2012). Woolf (2012) asserted that the succession of depositional systems in the Lower Tuscaloosa Formation changes from source-to sink in response to both relative sea-level (RSL) fall and rise. During RSL fall, the mid-Cenomanian unconformity were formed along the base of incise valleys that sediments were cut and subsequently filled within the valley. Moreover, these incised valleys served as conduits that bypasses eroded sediments to deposit as shelf-edge deltas, while some of the sediments continued to cross over the shelf edge and deposited in deep-water environments as gravity flow deposits. Sources of theses gravity flow deposits may have transported through the East Texas Basin and crossed over shelf edges in the vicinity of present-day Houston, Texas (Ambrose et al., 2009). When the sediment supply exceeds the RSL rise rates, incised valleys were filled with aggraded sediments. These high sedimentation rates continuously fed tide and wave-dominated deltas and deepwater gravity systems. The continental shelf edge in the Late Cretaceous was located at the Edward reef trend southeastward of the East Texas Basin (Hentz et al., 2014). Therefore, this study is focused on lowstand wedges in response to sea-level fall. Lowstand wedges consist of progradational packages seaward of the shelf edge and incised-valley fills on the shelf or upper slope.

A lowstand incised-valley is a topographically elongate feature as a result of fluvial erosion, cutting into underlying highstand strata during sea-level fall (Holbrook and Bhattacharya, 2012). The fluvial incision and aggradation are mainly controlled by the relationship between fluvial equilibrium and slope gradient (Holbrook et al., 2006). The incised valley is associated with an extreme basinward shift in facies (Van Wagoner and Mitchum, 1990). Incised-valley fills, which onlap onto sequence boundaries, are capped by a transgressive surface of erosion and flooding surface with subsequent transgression. The incised valley serves as a conduit for bypassing eroded sediments basinward to the mouth of the valley (Zaitlin et al., 1994; Reading, 1996). Vail and Wornardt (1991) and Zaitlin et al. (1994) proposed that the filling of the incised-valley begins at the mouth of the incised-valley as fluvial deposition during the late lowstand and subsequent estuarine deposits, migrating landward during the sea-level rise.

In contrast, Strong and Paola (2008) proposed that incised valleys form and evolve continuously throughout both sea-level fall and rise, observed within the experimental flume approach. In response to RSL fall, incised valley can form two types of erosional unconformities, which are broad planar erosional surfaces that form during slow RSL fall and narrow valleys that form during rapid RSL rise. Because slow sea-level fall provide more time for a basin to maintain an equilibrium state, deposition and erosion are uniform across the basin. In contrast, rapid sea-level fall causes a disequilibrium response, producing a well-defined incised valley. After that, both types of erosional surfaces are continuously widened and filled during RSL rise. Although these dynamic reshaping and filling cause a similarity in shape between stratigraphic valleys topographic valleys, stratigraphic incised-valley surfaces represent a persistent over some time intervals. Accordingly, stratigraphic incised-valley surfaces are important in sequence stratigraphy as a common type of sequence boundaries. However, interplay of dynamic erosion and deposition during base-level cycles may cause composite surfaces that are highly diachronous along strike in proximal areas of the basin. The formation of composite surfaces is characterized by lateral shifting of formative scour on the sequence boundary that younger valleys were active above the older valley strata and buried the sequence boundary (Holbrook 1996, 2001, 2010). Supported this idea, Blum and Price (1998) proposed that four crosscutting alloformations within an extent Quaternary fill were formed by multiple episodes of lateral migration, aggradation, and floodplain abandoned with soil formation during the sea-level fall, resulting in this composite unconformity at the base of valley fills. The numerical ages of these crosscutting stratas show that the sequence boundary was sequential and diachronous. In conclusion, although the validity of a sequence boundary as a synchronous surface is still debated, a sequence boundary tends to be agree on its value as an indicator of a period of base-level fall, accompanied by significant sediment bypass (Porebski and Steel, 2006)

The fluvial style within the incised-valley is controlled by various factors such as sediment supply, sea-level, and gradient (Zaitlin et al., 1994; Dalrymple, 2006; Holbrook et al., 2006). Dalrymple (2006) proposed that the formation and filling of incised valleys depend on the interplay of various factors, including sediment supply, slope of the river, water discharge. The formation of incised valleys occurs when the transport capacity of rivers exceeds the carried sediments (Holbrook et al., 2006). The primary mechanism of valley formation is an increase of the river slope in response to RSL fall or differential uplift. However, Blum and Törnqvist (2000) asserted that valley formation can be rather depended on changes in climate, causing a change in vegetation cover and rate of erosion. Strong and Paola (2008) stated that valleys are progressively less incised downdip, resulting in a decrease in depth of valleys. The transition from incised to non-incised system is represented by a rapid widening of the fluvial floodplain as it passed from confined valleys. A downdip decrease in valley depth is caused by decreasing rates of subsidence in the updip, leading to increasing rates of RSL fall updip. Accordingly, while fluvial incision increases upstream, the downstream is likely filled with eroded sediments from the upstream.

Dalrymple (2006) proposed that substantially diverse of valley fills, which vary from fluvial conglomerates and debris flows to fine-grained coastal and marine-deposits depend on the several factors. Accommodation and sediment supply principally cause changes in the valley-fill architecture along the entire length of the valleys during a RSL cycle (Holbrook et al., 2006). Accordingly, slow rates of RSL rise and high sediment supply seem to promote more aggradation near the lowstand mouth of the valley and at the initial highstand shoreline. In contrast, more rapid rates of sea-level rise lead to more retrogradational stacking of valley fills.

Transgressive system tract

The transgressive system tract is characterized by the regional upward-fining and deepening profile, resulting from the extensive retrogradational stacking pattern (Figure 3.1). The transgressive system tract forms during the stage of the sea-level rise, bounded by the transgressive surface at the base and the maximum flooding surface at the top (Catuneanu, 2006).

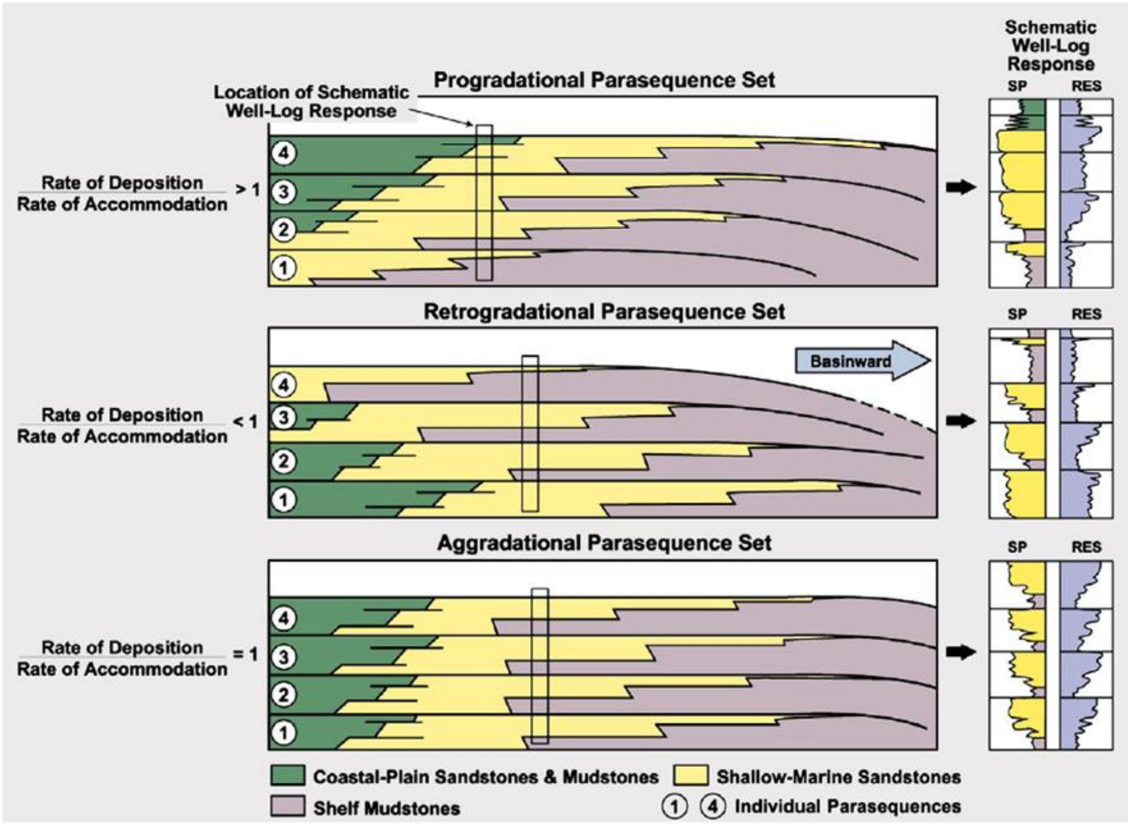

Figure3.1: Cross-section and well-log expression of stacking patterns in parasequence set in response to interplay between depositional and accommodation rates, modified from Van Wagoner (1990).

STRATIGRAPHIC SURFACES

Stratigraphic surfaces mark shifts in depositional system through time in response to the interplay of base-level changes and sedimentation. The correlation of stratigraphic surfaces provides a chronostratigraphic framework for facies analysis. According to genetic sequence by Galloway (1989), stratigraphic surfaces in each sequence consist of a sequence boundary, maximum flooding surface, and a transgressive surface.

Sequence boundaries

The sequence boundary (SB) is a subaerial unconformity or non-depositional surface, typically caused by incision by fluvial processes within an incised-valley during sea-level fall. The sequence boundary occurs at the base of lowstand incised-valley fills, typically ranging from fluvial conglomerates and debris flows to fine-grained marine deposits, resulting in thick blocky to slightly upward-finning profiles on both log responses and core samples (Reading, 1996; Dalrymple, 2006) and at the top of the younger highstand deposits, cut by subsequent incised-valley fill deposits (Vail and Wornardt, 1991). This erosional surface is a time-transgressive surface, which is never fully subaerial exposed along its length because incised-valleys are incised and locally covered throughout regressive and transgressive cycle (Holbrook and Bhattacharya, 2012).

Transgressive surface

The transgressive surface occurs at the top of incised-valley fill deposits of a lowstand system and coincides with the sequence boundary at the top of highstand deposits. This surface is formed as a marine flooding surface, that forms as the result of the rate of sea-level rise being greater than the rate of the sedimentation rate.

Maximum flooding surface

The maximum flooding surface (MFS) is defined as a top of a typically upward-fining stacking section of the transgressive systems tract, separating from prograding (HST) strata above (Van Wagoner and Mitchum, 1990). Catuneanu (2006) demonstrated that a MFS is typically formed as a conformable and regional surface, characterized by high GR-log responses, reflecting an increase of organic matters and radioactive elements at its maximum landward position of the shoreline. The maximum flooding surface is easy to identify because this surface is low diachronous along dip, representing low rates of sediment transport to the shelf and deep-water system (Catuneanu, 2006).

SEQUENCE STRATIGRAPHY OF THE UPPER CRETACEOUS SECTION IN ANDERSON AND CHEROKEE COUNTIES

According to the genetic sequence model (Galloway, 1989), deposits within Anderson and Cherokee Counties can be subdivided in the basal third- and fourth-order sequences, bounded by significant stratigraphic surfaces such as maximum flooding surfaces, transgressive surfaces, and sequence boundary. The Woodbine Group is a siliciclastic succession between the Washita Group at the base and the Eagle Ford Group at the top.

Buda Limestone

The Buda Limestone of the uppermost part of the Washita Group was deposited in a highstand system during the late Cretaceous middle Cenomanian (Ambrose et al., 2009). The 170-200-ft. Buda Limestone is characterized by low-constant values with a left GR (15 to 30 API units) and SP (-15 to -30 mV) deflection and extremely high values of resistivity logs (200-400 ohm-m), resulting in a sharp right deflection. These log responses are consistent with low-permeability, carbonate successions. The top of the Buda Limestone records either extensive erosion or a non-deposition surface. This unconformity is defined as the third-order sequence boundary (SB 10), dated at approximately 94 Ma (Haq et al., 1988; Ambrose et al., 2009). This sequence boundary is overlain by the upward-fining unit of the Maness Shale.

Maness Shale

The Maness Shale occurs in the upper part of the Washita Group and is middle Cenomanian in age. The lower half of the Maness shale is approximately 50 ft. thick, forming a transgressive system tract within a third-order sequence overlying the highstand Buda Limestone (Ambrose et al., 2009). The thickness of the Maness Shale varies and decreases eastward and westward to the Sabine Uplift and Woodbine outcrop, respectively. The lower Maness Shale is characterized by an upward-fining stacking pattern of a transgressive systems tract. The top of the Maness shale is identified by the Maximum flooding surface (MFS 10), dated at approximately 93.5 Ma (Haq et al., 1988; Ambrose et al., 2009). The maximum flooding is a regional and conformable surface, defined by rightward deflections of GR and SP logs.

Woodbine Group

The top surface of the Woodbine Group in this study is a maximum flooding surface (MFS 150), occurs at the top of a transgressive systems tract at the base of the Eagle Ford Group. This surface coincides with a regionally extensive, early Turonian third-order maximum flooding surface, dated at approximately 91.5 Ma (Haq et al., 1988; Ambrose et al., 2009). The thickness of the Eagle Ford Group also decreases toward the Sabine Uplift and the Woodbine outcrop. The Woodbine Group is directly overlain by the Austin Chalk in the southeastern part of the East Texas Basin near the Sabine Uplift. The base of the Austin Chalk is represented by a third-order sequence boundary of middle-to-upper Turonian age. Therefore, the approximate period of the Woodbine deposition is approximately 1.5 m.y., beginning from ~93.5 Ma to 92 Ma. Each deposition of the fourth-order sequence occurs over a period of approximately 110 k.y (Ambrose et al., 2009).

On the basis of genetic sequence model, the Woodbine Group in Anderson and Cherokee Counties is composed of highstand, lowstand, and transgressive deposits with in each sequence, bounded by maximum flooding surfaces. Each fourth-order sequence consists of a sequence boundary, transgressive surface, and maximum flooding surface. The sequence boundary is defined at the top of upward-coarsening unit of a highstand system and along the base of incised-valley fill of the lowstand systems. The sequence boundary represents widespread erosion and subaerial exposure during sea-level fall. The highstand deposits were eroded by the incised-valley, indicated by blocky log responses. The sequence boundary coincides with the overlying transgressive surface. The transgressive surface is identified at the contact between the underlying highstand deposits and incised-valley fill of lowstand deposits and the overlying upward-fining sequence of the transgressive system tract. Maximum flooding surfaces are inferred at the top of the transgressive systems tract.

Fourth-order sequences were interpreted from the top of Buda Limestone (SB10) to the lowest part of the Eagle Ford Group (MFS 150), reaching a maximum of preserved 14 cycles along the basin axis. They decrease eastward to the west flank of the Sabine Uplift and westward to the Woodbine outcrop with a minimum of three cycles and six cycles, respectively. Moreover, because of the Sabine Uplift in the eastern part of the study area, the top of the Woodbine Group shows unconformity surfaces, consisting of multiple depositional pinch outs toward Eagle Ford Group and Austin Chalk. The highstand deposits within the fourth-order sequences range from 15 to 120 ft. thick, overlain by transgressive deposits that vary from 10-50 ft. thick. In contrast, the incised-valley fills of the lowstand system are as much as 120 ft. thick near the basin axis. The great thickness of the incised-valley fills indicated a fall of relative sea level of no less than 215 ft. (Ambrose et al., 2009). Moreover, Ambrose et al. (2009) and Hentz et al. (2014) proposed that a high magnitude of fluvial incision and significant increase of accommodation are caused by salt mobilization and influx of abundant coarse-grained sediments during the early Late Cretaceous. In addition, thickness of Woodbine fourth-order sequences decreases upward, which may be caused during a third-order transgressive system tract (Hentz et al., 2014).

Chapter 4: Core Description and Facies Interpretation

CORE ANALYSIS

Slabbed core samples in this study are from one well in northeastern Cherokee County, operated by the American Petroleum Cooperation (Figure 1.1). The total thickness of the slabbed core samples is 202 ft (3737-3939 ft), covering 195 ft of the Woodbine Group as described in Figure 4.1 to 4.5. In order to interpret facies and depositional systems in Anderson and Cherokee Counties, slabbed core samples are characterized and calibrated with spontaneous potential log (SP-log) responses. The slabbed core samples were examined based on lithology, stacking patterns, and sedimentary structures for these interpretations.

CORE DESCRIPTIONS

Sequence 1

Description

45 ft of the lowermost interval in the core from 3940-3895 ft represents the deposits of sequence 1, consisting of upward-coarsening succession at the base and the overlying upward-fining succession at the top (Figure 4.1). The lower section of this interval from 3930-3940 ft consists of interbedded calcareous mudstones and fine-grained sandstones. Sedimentary structures include thin (0.5-2 cm) laminated mudstones with small-scale ripples at the top, interbedded with thin (0.5-1 cm) to thick (1-4 cm) fine-grained sandstones with a sharp base as shown in Figure 4.1B. Moreover, there are few occurrences of soft-sediment deformation at the top of this lower section, which grade upward into upward-coarsening fine-to-medium-grained sandstones in the core interval from 3920-3930 ft The lower part (3925-3930 ft) of the overlying succession represents

thin beds (5-10 cm) of interbedded siltstones and very fine-grained sandstones with sharp bases. Laminations are commonly found in this interval with rare soft-sediment deformation. In contrast, the upper part of this overlying interval from 3925-3920 ft shows thick beds (10-20 cm.) of brown fine-grained sandstone in this facies with small-scale ripples, soft-sediment deformation, and distorted burrows. This unit is truncated by an upward-fining section of younger deposits with erosional base, extending from 3900-3910 ft. Within the uppermost interval of sequence 1, medium-grained sandstones grade upward to finer-grained sandstone and also exhibit a gradation in bedforms from low-angle cross-bedded strata into ripples and thin laminations. Soft-sediment deformation occurs within fine-grained sandstones that are interbedded with siltstone and mudstone.

The SP log in the lower interval exhibits a baseline to serrate response, overlain by an upward-coarsening serrate response (Figure 4.1). The uppermost part of the sequence 1 shows that the SP log records blocky-serrate to upward-fining signatures with a planar base. This SP response occurs above upward-coarsening log responses, eventually capped by the rightward deflection of a maximum flooding surface. Based on these sedimentary features and SP-log responses, the sequence 1 represents prodelta deposit, the younger delta front deposits, and the youngest distributary channel deposits.

Sequence 2

Description

The core interval from 3860-3895 ft records deposits of sequence 2, consisting of 35 ft of overall upward-coarsening successions as shown in figure 4.2. The lower section of this interval from 3880– 3895 ft comprises of upward-coarsening successions of interbedded siltstones and brown to purple, very fine to fine-grained sandstone beds

(Figure 4.2D). Moreover, the thickness of each bed within this succession is also thicker upward from 5-10 cm to approximately 15 cm. Laminations are commonly observed through entire succession. However, soft-sediment deformation and distorted *Planolites* burrows are common at the top of this succession (Figure 4.2E), overlying by overall upward-coarsening intervals of very fine to fine-grained sandstones from 3860-3880 ft. This upper section consists of the interbedded, laminated siltstones and mudstones, grading upward into very fine to fine-grained sandstones with small-scale current ripple (Figure 4.3D) and minor soft-sediment deformation (Figure 4.2B, C). Moreover, distorted *Planolites* burrows are found in the upper part of these intervals as shown in Figure 4.3C. A paleosol is developed at the top of the deposit, characterized by thin clay-coating and red, iron-rich stained surfaces.

Well log patterns in sequence 2 interval exhibit upward-coarsening and serrate signatures, corresponding to a decrease in clay content (Figure 4.2). According to sedimentary characters and well log patterns, sequence 2 represents delta front deposits, overlain by crevasse splay deposits.

Sequence 3

Description

The core interval from 3825 – 3860 ft represents deposits of sequence 3, which is contrast with the sedimentary structures of sequence 1 and 2 as previously described. The core record primarily thick (30 ft) and poorly sorted sandstones with an erosional base, extending approximately from 3825 to 3855 ft (Figure 4.3). These deposits are pebble conglomerates to coarse-grained sandstones, slightly grading upward into crossbedded, medium-grained sandstones and ripple-laminated sandstones. The erosional base of these successions is above burrowed, very fine to fine-grained sandstones of highstand origin, and is directly overlain by conglomerate to coarse-grained sandstones. These deposits are inferred to have eroded older highstand delta-plain and distal-deltaic deposits.

SP log responses of this interval are blocky to slightly upward-fining with a sharp base. This characteristic demonstrates that there is an abrupt change in grain size from underlying highstand deposits to lowstand deposit. Base on sedimentary structures and log responses, sequence 3 represents incised valley fills which cut down to the underlying deltaic deposits of the highstand system.

Sequence 4

Description

The core interval from 3770 - 3820 ft records sequence 4, consisting of overall upward-coarsening successions at the base and 45 ft. thick of coarse-grained sandstones at the top (Figure 4.4). The lower section of this interval comprises of upward-coarsening succession of interbedded mudstones and siltstones with lamination and small-scale ripples at the top. The grain size of the lower section grades upward into upward-coarsening successions of interbedded siltstones and very fine to fine-grained sandstones beds similar to those characteristics observed within the sequence 1 and 2. Sedimentary structures of this succession are lamination at the lower part and small-scale ripples, soft sediment deformation at the top, overlain by primarily thick and poor sorted sandstones with erosional base (Figure 4.4B). These thick beds consist of pebble conglomerates to coarse-grained sandstones, slightly grading upward into cross-bedded, coarse-medium grained sandstones and ripple-laminated sandstones.

SP log response of sequence 4 are upward-coarsening to serrate at the lower section and the overlying sharp left deflection as a blocky to slightly upward-fining. These responses reflect a change in clay contents from the higher value at the base to lower value at the top, representing abrupt change in depositional systems. Based on the core samples and log responses, sequence 4 represents prodelta deposits and the overlying delta front deposits, truncated by incised-valley fills.

Sequence 5

Description

The core interval from 3735-3780 ft represents overall upward-coarsening succession of sequence 5, overlain by carbonates of Austin Chalk. The lower section from 3740-3770 ft of the interval consists of overall upward-coarsening successions of thin beds (1-2 cm) of interbedded mudstones and siltstones (Figure 4.4 D), slightly grading upward into very fine and fine-medium grained sandstones. Sedimentary structures of this succession are small-scale ripples at the base and soft-sediment deformation and distorted burrows at the top (Figure 4.5B, C). These upward-coarsening successions are overlain by the Austin Chalk, which contains abundant of shell fragments and burrows. SP log responses exhibit upward-coarsening to serrate profiles. According to both core samples and well log patterns, sequence 5 represents prodelta and delta front deposits.

FACIES INTERPRETATIONS

Based on core samples and SP log responses, Woodbine sediments in Anderson and Cherokee Counties are divided into five facies: (1) Prodelta; (2) Delta front; (3) Distributary channels; (4) Crevasse splay; and (5) Incised valleys. Woodbine sediments deposited in a deltaic environment during highstand periods, truncated by incised-valley fills during lowstand periods. A delta is a partially subaerial environment where deposition is occurred by rivers as the flow enters a standing body of water. A delta is typically defined by a progradation of coarsening upward facies succession from muddier facies of the prodelta into the sandier facies of the delta front and mouth-bar depositional systems (Bhattacharya, 2006). The type of deltas is classified by the relative contribution of fluvial-, wave, or tidal process during the deposition (Fisher, 1969). Within the study area, fluvial dominated delta is common depositional systems, which rivers reach the basin and deposit sediments beyond the shoreline.

The delta profile can be divided on the basis of a process terminology into (1) delta plain, which is the large subaerial zone dominated by river, (2) delta front, which is dominated by the interaction between fluvial and basinal process, and (3) prodelta, identified by a slow rate of fine-grained deposition at the toe of delta-front (Galloway, 1975; Reading, 1996).

1.) Prodelta

The prodelta facies is characterized by laminated to thin-bedded of mudstones and massive to well-stratified of siltstones, deposited by suspension in a stable zone (Reading, 1996) as observed within the core intervals from 3930-3940 ft and 3760-3770 ft (Figure 4.1, 4.5). Laminated mudstones and fine-grained sandstones commonly reflect fluctuations in river sediments carried in buoyant plumes, unlike abundance of bioturbation of the basin floor sediments (Bhattacharya, 2006). The SP log response is a baseline to serrate profile, overlying the rightward deflection of SP-log profiles in response to a high mud contents (Figure 4.1). These characteristics suggest suspension sedimentation, resulting in laminated, silty mudstone beds as describe in Figure 4.1 and 4.5. In overlying strata, these features are contorted, recording soft-sediment failure and slumping in response to the overlying pressure and high sedimentation rates (Bhattacharya, 2006). Moreover, as observed in sequence 1 and 4, calcareous sediments in laminated mudstones typically indicate a depositional system that is near marine environments (Bhattacharya, 2006).

2.) Delta Front

The delta-front facies of the Woodbine deposits are identified by upward-coarsening successions of interbedded siltstones and very fine to fine-grained sandstone beds and upward-coarsening responses on the SP log (Van Wagoner and Mitchum, 1990), extending approximately from 3755-3765 ft., 3880-3895 ft, and 3920-3930 ft as shown in Figure 4.1, 4.2, and 4.5. A delta front is an area where fluvial sediments reach the basin and interact with basinal processes (Reading, 1996). According to Bhattacharya (2006), fluvial dominated delta front commonly consists of a complex framework of distributary channels and mouth-bars, forming depositional lobes. Delta front deposits mainly preserve coarser sediments, which can be extended up to several kilometers wide. Current ripples and cross bedding are common in delta front facies, representing deposition from rapidly decelerating unidirectional flows in distributary and mouth-bar environments (Reading, 1996). Moreover, thin beds of sandstones as observed in delta front deposits record multiple, sediment-laden discharges on a slope downdip of the distributary-channel terminus. However, these delta-front deposits are commonly truncated by distributary-channel facies, with the result of soft-sediment deformation recording compaction (Reading, 1996).

3.) Delta plain

The delta plain is an extensive low gradient area, consisting of a wide variety of non-marine to brackish environments, including distributary channels and interdistributary areas (Reading 1996; Bhattacharya, 2006). Upper delta plains are typically similar to alluvial environments because there is no effect from basinal processes. However, interdistributary areas, including swamps, marshes, and lake are more widespread and channels are downdip bifurcated. Like upper delta plains, lower delta plains also dominated by fluvial process, but the river mouth and distributary-bar deposits are influenced by marine processes, causing salt-wedge penetration. (Reading, 1996).

3.1) Distributary channel

The distributary channel facies of the Woodbine deposits are inferred from an overall upward-fining grain-size profile with an erosional base, similar to characteristics of fluvial channels such as channel lags and low-angle cross-bedded strata, ripples, and thin laminations. (Bhattacharya, 2006). In the Woodbine core from 3900-3910 ft, the distributary channels sediments grade upward through cross-bedded sands into ripple-lamination with silt and clay alternation.

Delta-plain channels are forced to bifurcate into several distributary channels at a point where the channel cannot continue to cut through distributary mouth bar, surrounded by wide areas of interdistributary bays on the delta plain, including swamps, marshes, and lakes (Reading, 1996). According to Bhattacharya (2006), the bifurcation patterns depend on numerous factors such as slope, river discharge, and water depth. In fluvial dominated delta, low gradient and high discharge usually cause multiple bifurcations, reflecting a high control of friction on sediment dispersal. Moreover, these distributary channels may exhibit a wide range of sizes and shapes in different areas on delta plain (Reading, 1996). Although distributary channels in non-marine delta plain are entirely similar to rivers, they tend to be single-story rather than multi-story, compared to valley fills. Unlike fluvial channel, the distal parts of distributary channels may be influenced by basinal processes, resulting in saltwater penetration. Moreover, distributive channel systems generally decrease water discharge, channel width, and channel depth in response to high frequency of avulsion (Bhattacharya, 2006). The SP log records blocky-serrate to upward-fining signatures above upward-coarsening log responses, indicating progradational stacking pattern of delta-plain deposits (Figure 4.1).

3.2) Interdistributary area: Crevasse splay

Interdistributary bays is areas between distributary channels on delta plains, consisting of levees, crevasse splays, swamps, marshes, and enclosed water bodies, which are commonly lakes in upper delta plains and lagoons in lower delta plains (Elliott, 1974; Bhattacharya, 2006). Interdistributary bays typically have less than ten meters thick of coarsening-and fining upward facies successions of muddier deposits. These areas are commonly filled by overbank spilling of thin coarsening or fining succession of fine-grained sandstones during flood periods, known as crevasse splays (Bhattacharya, 2006).

Crevasse splays are discrete lobes of silty or sandy sediments, which extend downward from the levee and spread on the floodplain in response to a flood process (Reading, 1996). Vertical facies of crevasse splays show upward-coarsening successions and an increase of sand layers, reflecting migration and avulsion of adjacent channels

(Bhattacharya, 2006). Similar to those described by Reading (1996), crevasse splay deposits of the Woodbine Group in this study are characterized by overall upward-coarsening intervals of very fine to fine-grained sandstones, extending approximately from 3865-3875 ft and 3750-3755 ft as shown in Figure 4.1 and 4.3. Their sedimentary features include sheet sands in the bay muds and may in levee sequences, parallel lamination, and current ripple lamination, overlying by ponded fine sediments or vegetation (Elliott, 1974). Similar to those described by Elliott (1974), crevasse splay deposits of Woodbine successions show lamination of siltstones and mudstones, grading upward into fine-grained sandstones with small ripples as seen in Figure 4.2B.

Well log patterns in crevasse-splay deposits exhibit upward-coarsening and serrate signatures, corresponding to a decrease in clay content. These crevasse splay deposits are typically flanked by distributary channel deposits in a delta plain environment.

4.) Incised valley

An incised valley is a fluvial-eroded, elongated topographic low, marked by an abrupt shift of facies across a regional erosional surface at its base (Boyd et al., 2006). Valley fills, commonly consisting of fluvial conglomerates and debris flows to fine-grained marine deposits are much thicker than associated delta-front succession because of multi-story sandstones. Incised-valley deposits in this study are characterized by primarily 20-30 ft thick and poorly sorted sandstones with an erosional base, extending from 3780-3800 ft and 3835-3855 ft (Figure 4.3, 4.4). These incised-valley deposits eroded underlying highstand delta-plain and distal-deltaic deposits, causing an abrupt change in facies and a decrease of mud contents from underlying highstand deposits to lowstand deposit as shown in sharp left deflection of SP log responses.

Moreover, incised valleys form a tributive rather than a distributive pattern, which is larger than a single channel form (Bhattacharya, 2006). Although fluvial and estuarine sediments typically begin to deposit at the mouth of the incised-valleys and expand landward during sea-level rise (Zaitlin et al., 1994), there is no estuarine and marine deposits shown in the Woodbine incised-valley fills within the study area. This is because the proximal part of incised-valley tends to have low basinal influence (Dalrymple, 2006), resulting in limitation of transgressive estuarine deposits to extend in the innermost reach of the incised valley (Boyd et al., 2006).

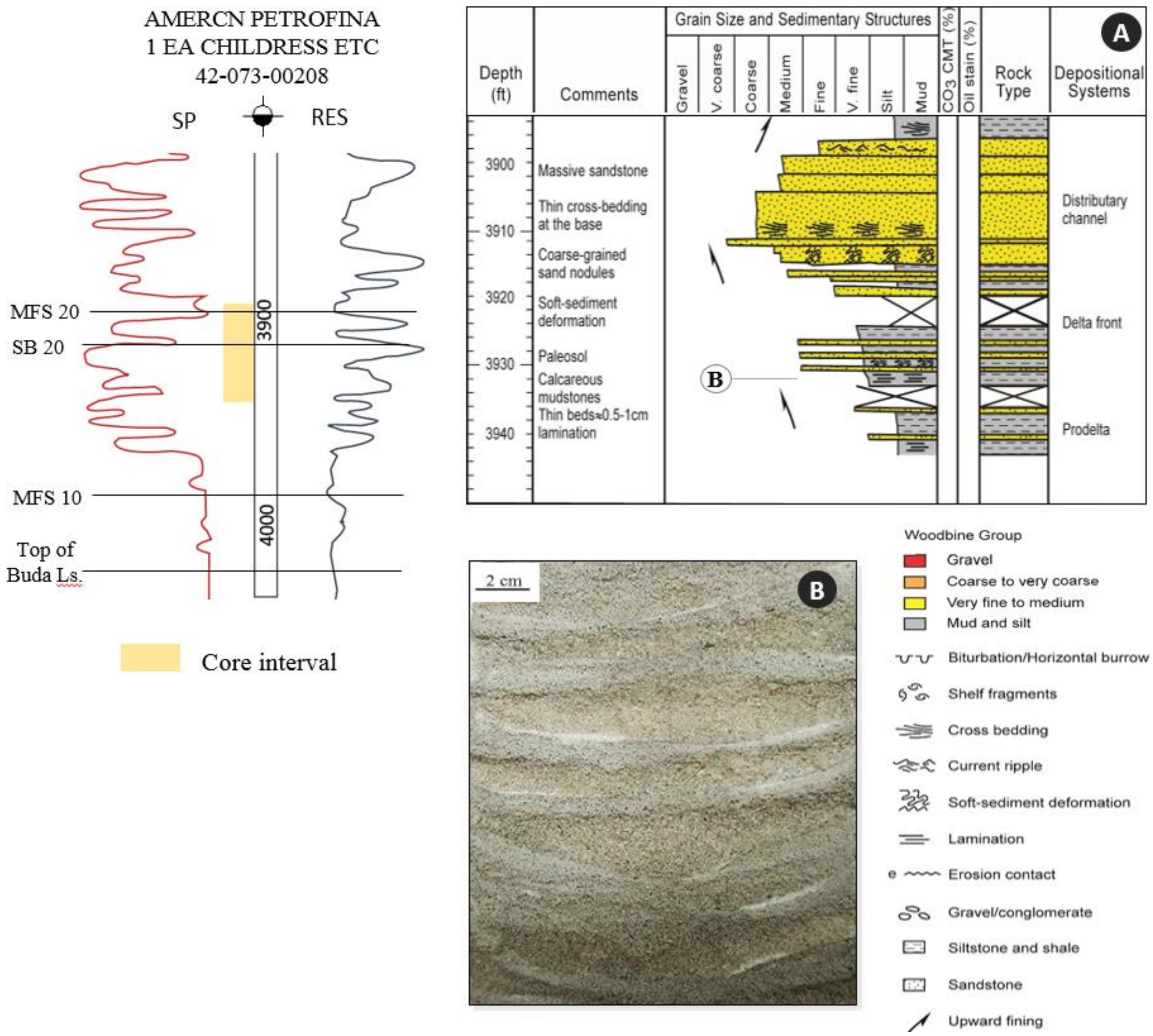

Figure 4.1: Core description and photographs of Sequence 1 from the well in northeastern Cherokee County, operated by the American Petroleum Cooperation (Fig. 1.1). (A) Description and log responses of interval from 3890 to 3940 ft. (B) Interbedded calcareous mudstones and fine-grained sandstones in prodelta at 3,930 ft.

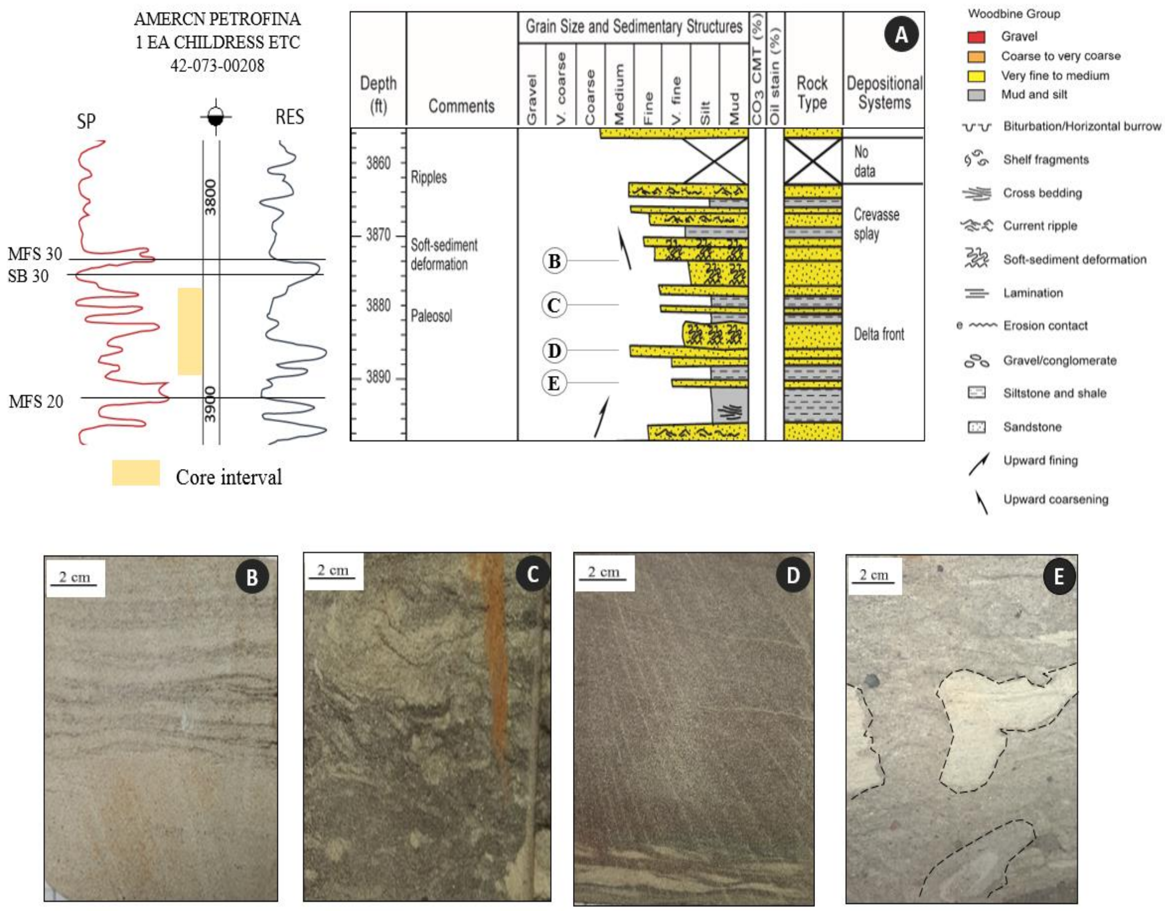

Figure 4.2: Core description and photographs of Sequence 2 from the well in northeastern Cherokee County, operated by the American Petroleum Cooperation (Fig. 1.1). (A) Description and log responses of interval from 3860 to 3895 ft. (B) Current-ripple stratification in crevasse-splay deposits at 3875 ft. (C) Soft-sediment deformation in crevasse-splay at 3,880 ft. Upward-coarsening succession of delta-front deposits overlying prodelta deposits, showing (D) Brown to purple, fine-grained sandstones of upper delta front at 3,885 ft. (E) burrowed fine sandstones with soft-sediment deformation at 3,890 ft.

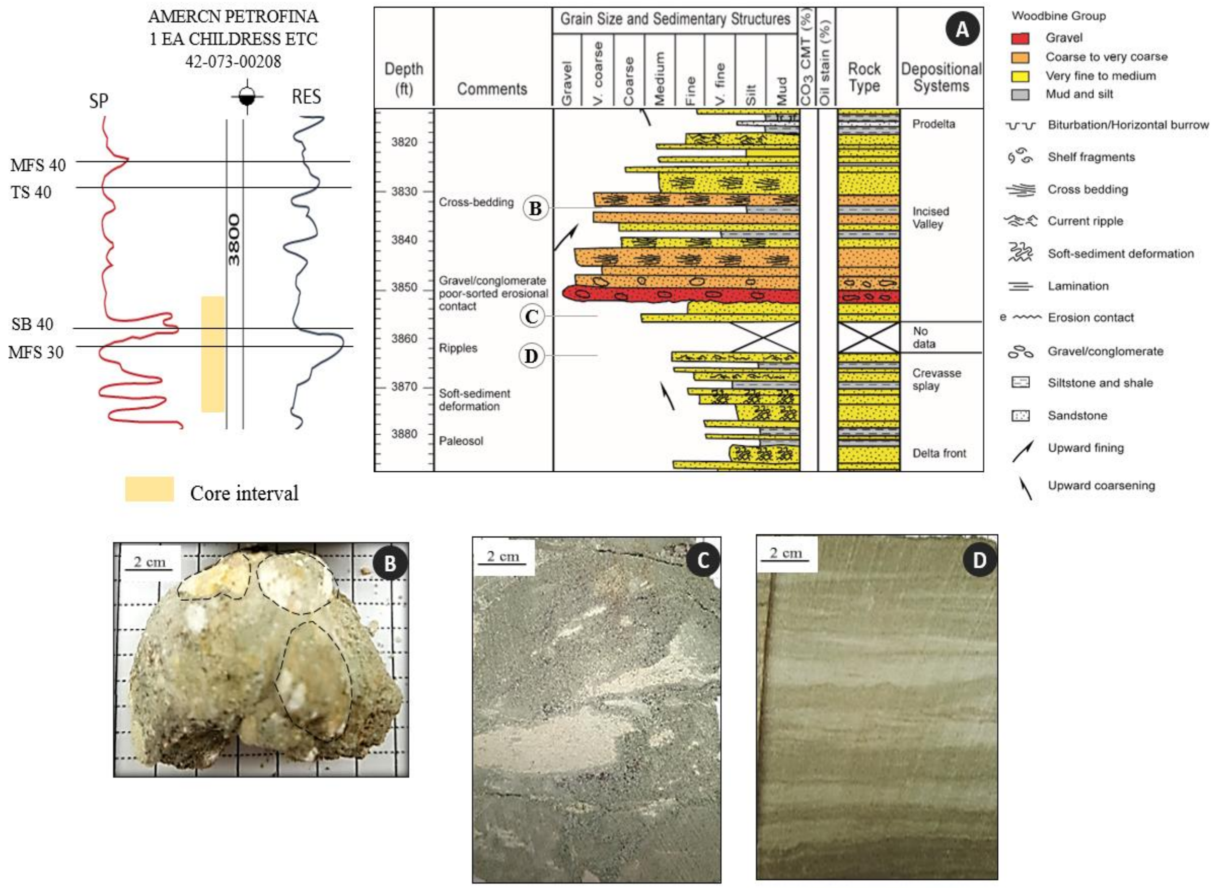

Figure 4.3: Core description and photographs of Sequence 3 from the well in northeastern Cherokee County, operated by the American Petroleum Cooperation (Fig. 1.1). (A) Description and log responses of interval from 3820 to 3880 ft. (B) Coarse-grained sandstones with pebble conglomerates from the base of the incised-valley at 3835 ft. (C) Upper part of crevasse-splay deposits with *Planolites* burrows in crevasse splay at 3855 ft. (D) Current-ripple stratification in crevasse-splay deposits at 3863 ft.

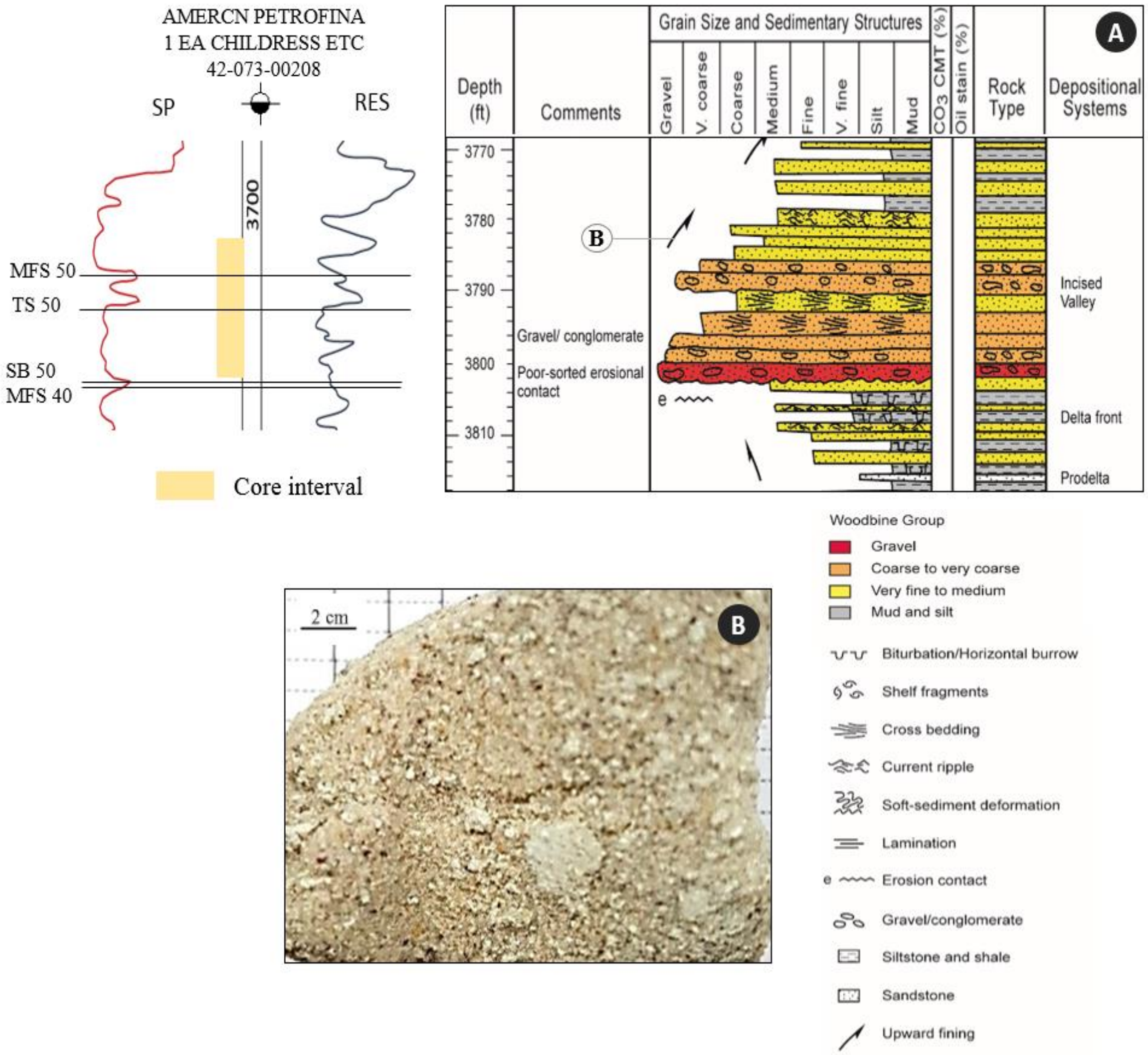

Figure 4.4: Core description and photographs of Sequence 4 from the well in northeastern Cherokee County, operated by the American Petroleum Cooperation (Fig. 1.1). (A) Description and log responses of interval from 3770 to 3815 ft. (B) poorly sorted sandstones of incised-valley deposits at 3,785 ft.

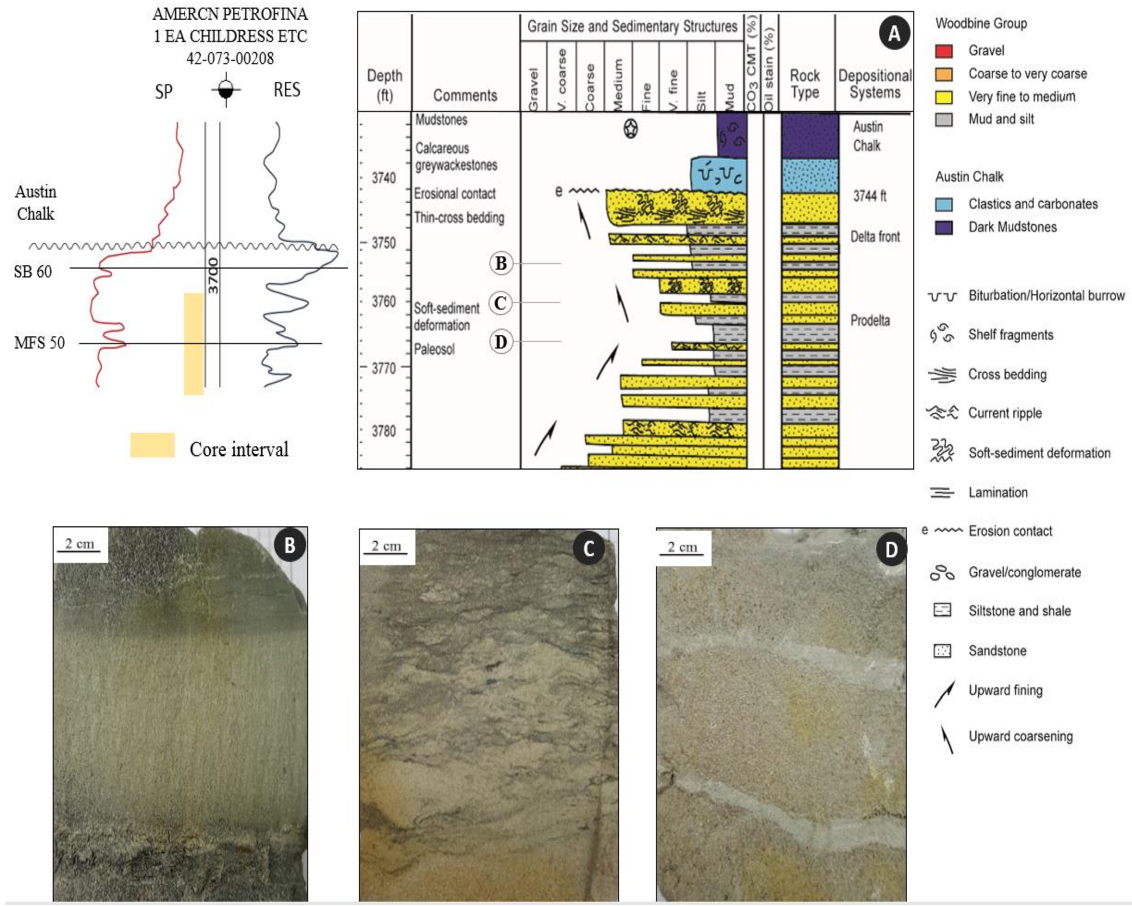

Figure 4.5: Core description and photographs of Sequence 5 from the well in northeastern Cherokee County, operated by the American Petroleum Cooperation (Fig. 1.1). (A) Description and log responses of interval from 3730 to 3785 ft. (B) Soft-sediment deformation in delta front deposits at 3,760 ft. (C) Interbedded calcareous mudstones and fine-grained sandstones in prodelta deposits at 3,765 ft. (D) Interbedded siltstones and very fine grained sandstones with sharp base in lower delta front at 3,755 ft.

Chapter 5: Gross-sandstone maps of Woodbine Lowstand and Highstand Deposits

There are only gross-sandstone maps of sequence 1 to sequence 5 that are supported by the cored well, located at the northeastern of Cherokee Country.

SEQUENCE 1

Description

Sequence 1 consists of HST, LST, and TST components, bounded by MFS10 and MFS 20 (Figure 5.1). Thickness of S1 ranges from 60 to 140 ft. The HST (50-80 ft) of the sequence 1 (S1) occurs between MFS10 at the base and SB20 at the top. However, the LST of S1 (40-100 ft) is bounded by SB20 at its base and transgressive surface at its top. The TST of S1 occurs between transgressive surface and MFS 20.

Highstand system tract

The HST of S1 is principally defined by overall upward-coarsening pattern (50-80 ft thick) on SP-log responses, locally consisting blocky to slightly upward-fining SP-log responses at the top. These blocky to upward-fining SP log responses tend to correspond with 15-35 ft thick of dip-elongate sandstone bodies (Figure 5.1 and 5.2). Moreover, the HST of sequence 1 represents a significant difference in log characteristics relative to the laterally adjacent log facies of S2, which are composed of thick (30-100ft) blocky SP log responses.

The gross-sandstone map exhibits, 15- to 35-ft, dip-elongate geometries that have anastomosing and slightly sinuous-tributive (Figure 5.2). These dip-elongate, north-south-trending sandstone bodies range in width from approximately 3 to 8 km. In the southern part of the study area, the gross-sandstone map displays a small lobe (1-2 km wide), downdip of these dip-elongate, areally limited sandstones. that pinch out into laterally extensive mud rocks defined by gross-sandstone values of 5-10 ft.

. Based on core samples, the lower section of sequence S1 displays an upward-coarsening succession of interbedded siltstones and very fine to fine-grained sandstone beds from 3920-3930 ft, including soft-sediment deformation and burrows (Figure 4.1B). This lower section is overlain by fine-to-medium-grained deposits with an upward-fining profile. Thesesandstones have low-angle, cross-bedded strata and an erosional base.

Lowstand systems tract

The LST in S1 is characterized by sharp-based, thick (40-100 ft), blocky to blocky serrate intervals with blocky to blocky-serrate SP log responses. These sandsones are inferred to truncate the underlying HST (Figure 5.1). SB 20 was correlated from the sharp bases of the lowstand deposits to the top of the underlying upward-coarsening succession, which is the HST of the S1 intervals. SB 20 represents a lateral change of facies from adjacent upward-coarsening intervals of HST within S1 to blocky LST of S2. The gross-sandstone map of LST of S1 shows a north-south orientation of distributive patterns that area approximately 10-20 km wide (Figure 5.3). Gross-sandstone values in the northern part of the study area are approximately 70 ft.

Interpretation

Highstand systems tract

The HST of S1 represents a fluvial-dominated deltaic system. Most of the area is characterized by overall upward-coarsening to serrate SP-log responses, similar to those interpreted as fluvial-dominated deltaic by Van Wagoner and Mitchum (1990). Blocky to slightly upward-fining log responses with planar base in the upper half of upward-coarsening log profiles are interpreted to be distributary channels that truncate underlying deltaic deposits (Figure 5.1). The gross-sandstone map is supported by the cored well at the northeastern of Cherokee County, located at the center of dip-elongate sandstone geometry (Figure 5.2). The core records two facies, including prodeltaic deposits and the overlying distributary channel deposits. Prodelta settings are characterized by an upward-coarsening succession of laminated to thin-bedded (1-3 cm) siltstones and fine-grained sandstones (Figure 4.1B), which commonly contain soft-sediment deformation that records sediment loading and high rates of sedimentation (Reading, 1996). Distributary channels of the S1 delta are defined by upward-fining successions of medium-to fine-grained sandstone beds, grading upward from cross-bedded sandstones into ripple-laminated of siltstone and mudstone. The distributary channel deposits contain clay clasts and abundant of organic fragments. However, unlike channels in alluvial plains, there is no presence of basal conglomerates and coarse-grained sandstones within distributary channels. Moreover, distributary channels contain thinner (15-30 ft thick) sand beds, compared to 40-100 ft thick of valley fills (Reading, 1996).

Although core samples, located in the northeastern part of the study area, represent distributary channel deposits, the gross-sandstone map shows that the central part of the study area is dominated by tributive and anastomosing patterns instead of downdip bifurcating patterns (Figure 5.2). The depositional system of S1 is similar to the anastomosing rivers in Middle Holocene distributary system in the Rhine–Meuse Delta, Netherlands described by Törnqvist (1993) and the Holocene Mississippi delta system (Galloway and Hobday, 1996). Principally distributive channels may also be partly anastomosing, when radial distributary channels are either interconnected or bypassed to rejoin downstream. The formation of anastomosing rivers is usually caused by frequent avulsion on a low floodplain gradient, resulting in aggradation of the channel belt and/or loss of channel capacity by in-channel deposition (Galloway and Hobday, 1996; Makaske, 2001). Törnqvist et al. (1993) proposed that the high aggradation rate of anastomosing rivers is mainly triggered by rapid rise of base level, leading to the longitudinal change in channel pattern. Moreover, the anastomosing pattern of the deltaic system can be formed by slow abandonment of old channels, resulting in old infilling channels and coexistence of younger channels. The anastomosis in continental settings and channels in deltaic environments are not fundamentally different in term of processes and sedimentation. However, marine or tidal processes may influence channel deposits of avulsions in near-coastal settings (Makaske, 2001) such as the tide-influenced Ganges-Brahmaputra delta (Bhattacharya, 2006) and Niger deltas (Fisher, 1969).

Lowstand systems tract

The LST of S1 represents an incised-valley system as shown in Figure 5.6, characterized by 40-100 ft thick of blocky to blocky serrate intervals with sharp base on SP-log responses. The elongate, topographic low of incised-valleys are marked by an abrupt shift of facies across a basal erosional surface (SB 20). As shown in the gross-sandstone map (Figure 5.3), incised valleys of S1 form a regionally tributive and distributive pattern in plan-view maps, preserved much thicker sandstones than associated deltaic successions. Incised valleys were formed by fluvial incision, cutting, reshaping, and contemporaneous buried by fluvial sediments throughout regressive and transgressive cycle as described by Holbrook and Bhattacharya (2012). Accordingly, incised valley fills are not only fluvial sediments, but also marine deposits such as estuarine sediments, which are deposited during sea-level rise (Allen and Posamentier, 1993). Moreover, when the filled sediments approached the thickness of the channel, rivers were unconfined by incised valleys and eventually formed a distributary pattern.

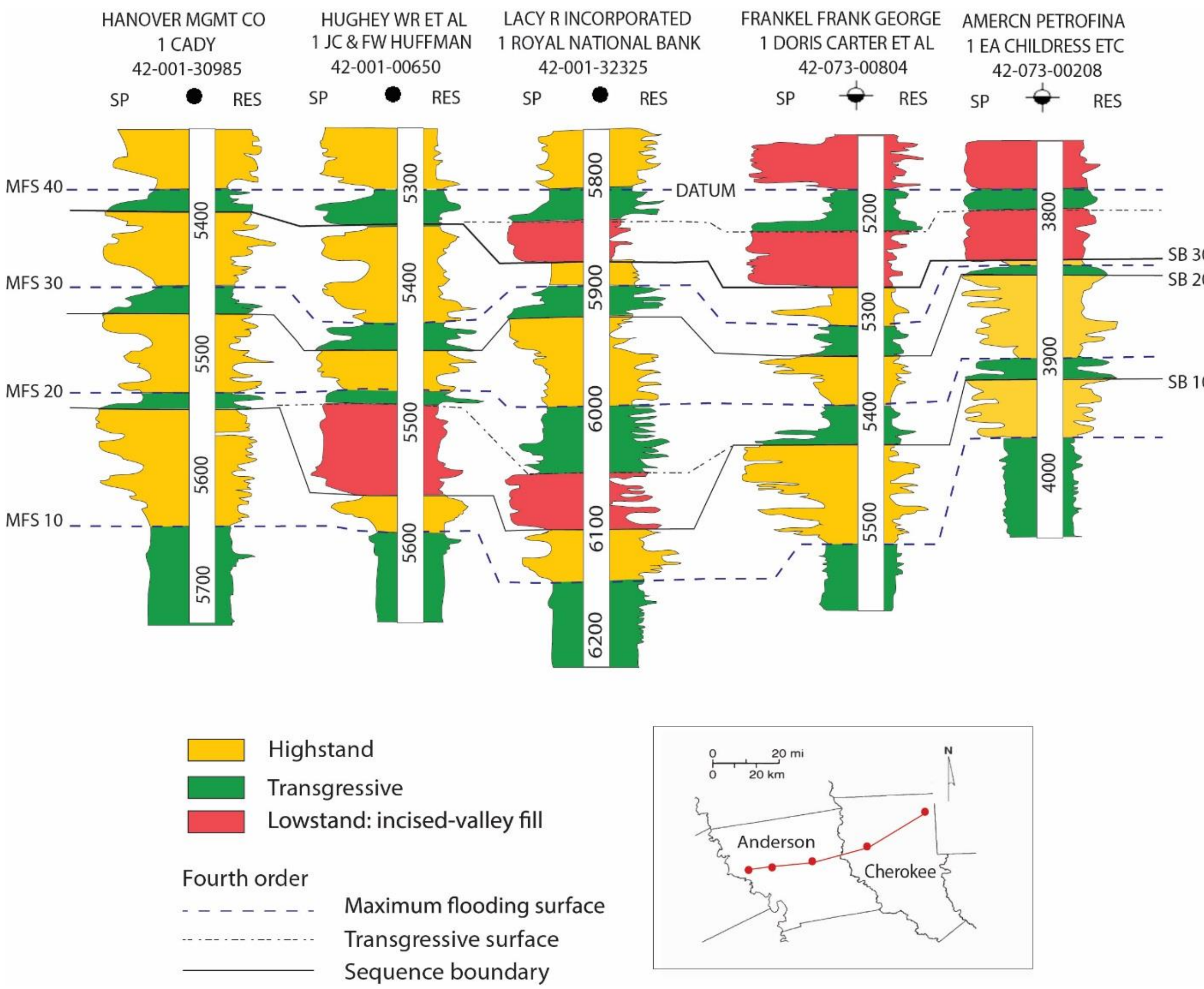

Figure 5.1: West-to-east stratigraphic section displaying Woodbine fourth-order sequence correlations from well logs, representing system tracts and depositional facies of sequence 1, 2, and 3. Datum is maximum flooding surface (MFS40).

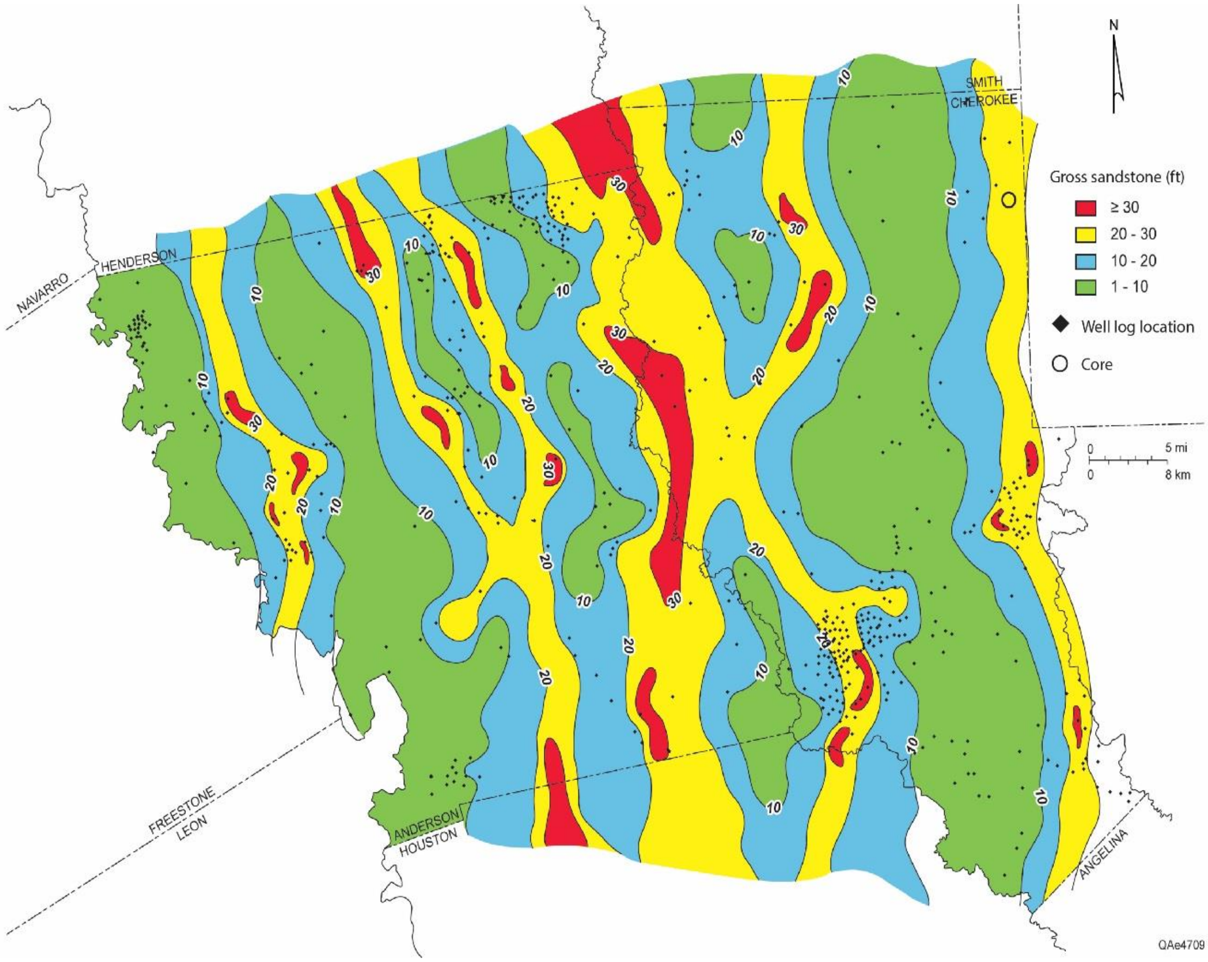

Figure 5.2: Gross-sandstone map of the Woodbine highstand deposits of sequence 1 in Anderson and Cherokee Counties. Thickness of S1 ranges from 60 to 140 ft, consisting of the 50-80 ft thick of HST and 40-100 ft thick of LST on SP log responses.

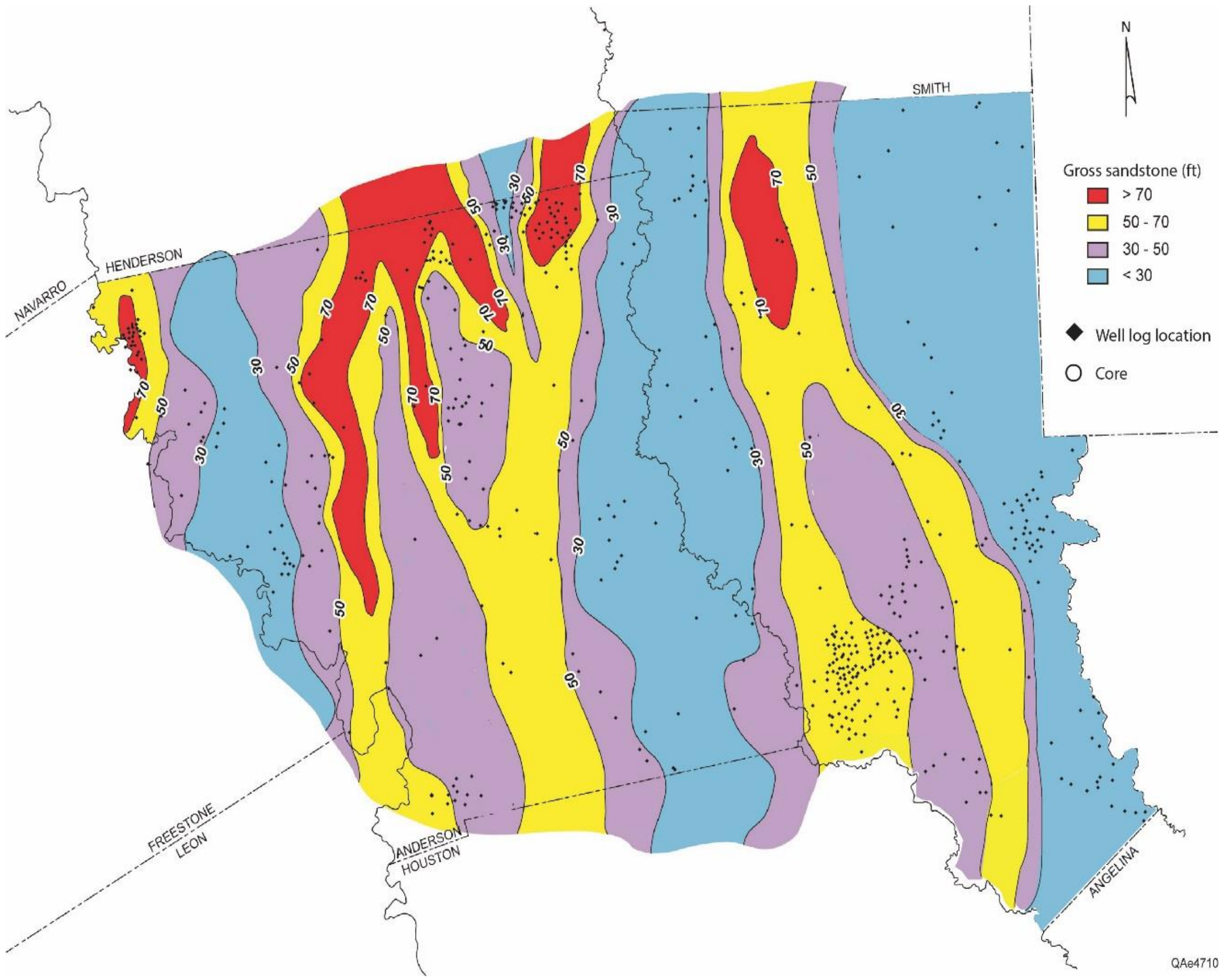

Figure 5.3: Gross-sandstone map of the Woodbine lowstand deposits of sequence 1 in Anderson and Cherokee Counties. Thickness of S1 ranges from 60 to 140 ft, consisting of the 50-80 ft thick of HST and 40-100 ft thick of LST on SP log responses.

Sequence 2

Description

Sequence 2 (S2) comprises HST, LST, and TST intervals, bounded by MFS20 and MFS 30 (Figure 5.1). Thickness of S2 ranges from 50 to 130 ft. The HST (30-80 ft) of the S2 is formed between MFS20 at the base and SB30 at the top. In contrast, the LST (30-100 ft) of S2 is bounded by SB30 at its base and transgressive surface at its top. The TST of S2 occurs between a transgressive surface and MFS 30.

Highstand systems tract

The Woodbine highstand deposits of the S2 interval are characterized by two principal log facies, ranging from approximately 30-80 ft thick on SP log responses as shown in Figure 5.1. Blocky (20-35 ft) to upward-fining with planar base on SP log profiles occur at the top of serrate-upward-coarsening log responses. The other commonly occurring log profile consist of upward-coarsening and serrate responses approximately 0-20 ft thick. In contrast to the HST of S1, wherein fluvial-dominated deltaic deposits exhibit anastomosing patterns (Figure 5.2), the gross sandstone map of HST of S2 (Figure 5.4) reveals north-south distributive patterns. The trend (25-30 km wide) of sandstone distribution in Cherokee County bifurcates downdip from approximately 15 km wide into 8 km. In contrast, 20-25 km wide of sandstone distribution in Anderson County shows narrow tributive pattern, which have a wide range of width from 4 to 8km. These sandstones are flanked by relatively more extensive muddy deposits with gross-sandstone values <10 ft thick.

The gross-sandstone map is supplemented by core samples from the well in the northeastern part of the study area, showing overall upward-coarsening intervals of very fine to fine-grained sandstones from 3865-3875 ft. This upward-coarsening succession overlies interbedded, laminated siltstones and mudstones with small current-ripple stratification (Figure 4.2B and 4.3D).

Lowstand systems tract

The lowstand deposits are characterized by thick (30-100 ft), blocky to blocky serrate intervals with sharp base on SP-log responses (Figure 5.1). SB 20 is defined as extending from the sharp bases of lowstand deposits to the top of the underlying upward-coarsening succession of the HST. SB 20 represents laterally different SP-log profiles of blocky LST of S2 and adjacent upward-coarsening intervals of HST. The gross-sandstone map of S2 shows a wide range of tributive and distributive pattern, extending from 10-20 km wide with northeast-southwest trending (Figure 5.5). Although the pattern of sandstone distribution is similar to that of sequence 1, there are lower and narrower gross-sandstone bodies (50-65 ft thick) in the western part of the study area, compared to approximately more than 60ft thick of the LST of S1. Moreover, the thickness of sandstones is less than those of the LST of S1. Within LST of S2, the high amount of sandstones is locally concentrated in Cherokee County.

Interpretation

Highstand systems tract

Like the HST of S1, the highstand deposits of S2 represent a fluvial-dominated deltacharacterized by overall upward-coarsening SP-log profiles similar to those described by Fisher (1969) for other HSTs. Blocky to upward-fining with planar base on SP-log profiles are interpreted as distributary channels that truncate underlying upward-coarsening facies of deltaic deposits (Reading, 1996). However, areas with low-gross sandstone values (5-15 ft) between dip-elongate, sandy depositional axes represent interdistributary-bay deposits. Interdistributary bays are areas between distributary channels, consisting of levees, crevasse splays, swamps, marshes, and enclosed water bodies (Elliott, 1974). Based on core samples from the S2 interval, upward-coarsening successions of siltstone and fine-grained sandstones are interpreted as crevasse splay deposits, extending further from the channel into floodplains.

Lowstand systems tract

The Woodbine lowstand deposits of S2 represent incised-valley fillscharacterized by thick, blocky to blocky serrate intervals with sharp base from SP-log responses (Van Wagoner and Mitchum, 1990). The incised valleys were formed by fluvial incision during sea-level fall and filled with sediments with subsequent sea-level rise. The formation and filling of incised valleys were continuous throughout the regressive and transgressive cycle. Accordingly, the erosional surface (SB30) was locally subaerial exposed and formed as diachronous surface as described by Holbrook and Bhattacharya (2012). Moreover, the gross sandstone map shows thicker and more extensive tributive pattern compared to a single channel form. Broad planar erosional surfaces were caused by extensive fluvial incision that formed during slow relative sea level (RSL) fall because a basin had more time to maintain an equilibrium state, providing conformable erosion and deposition (Strong and Paola, 2008).

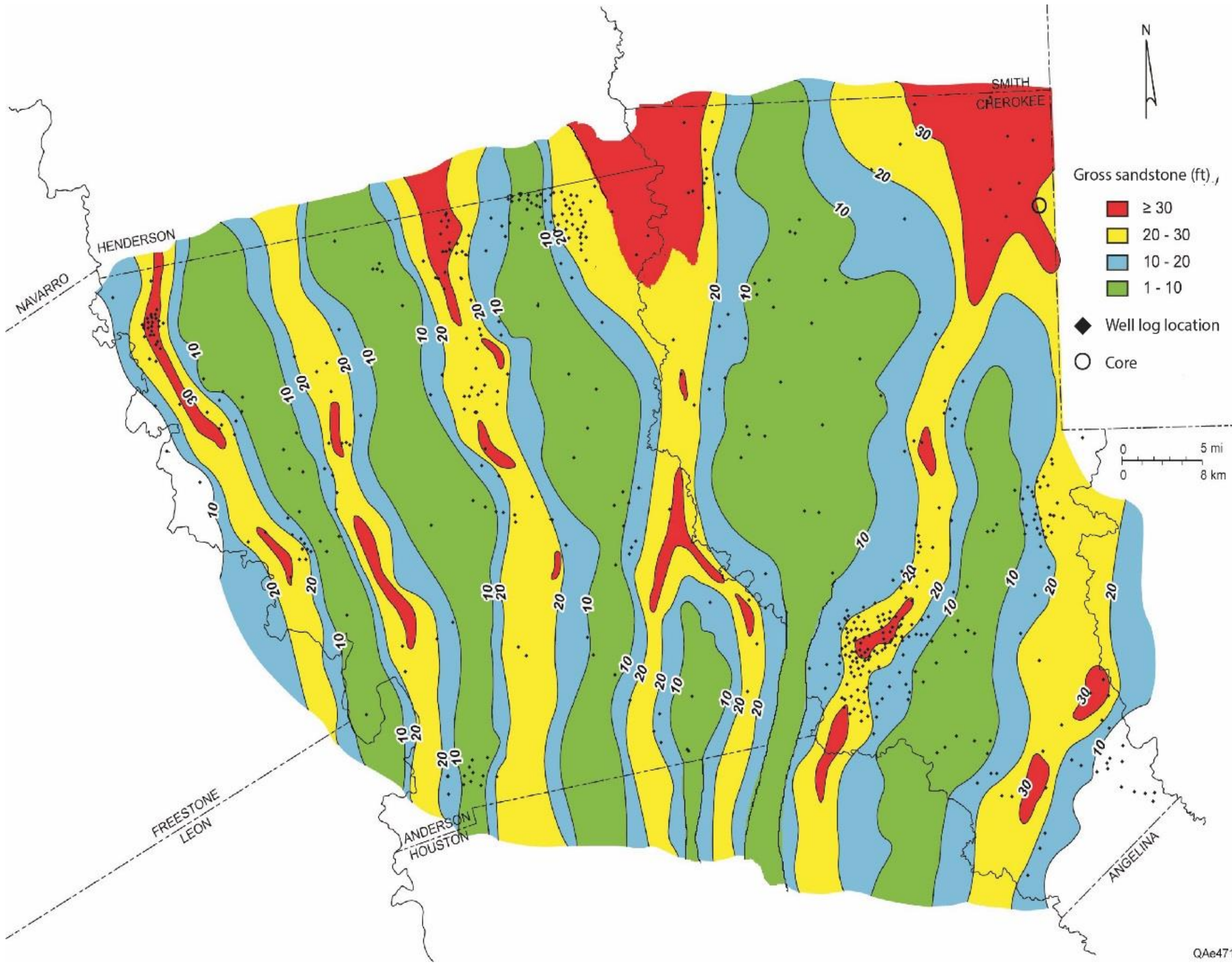

Figure 5.4: Gross-sandstone map of the Woodbine highstand deposits of sequence 2 in Anderson and Cherokee Counties. Thickness of S2 ranges from 50 to 130 ft, consisting of the HST (30-80 ft) and LST (30-100 ft) on SP log responses.

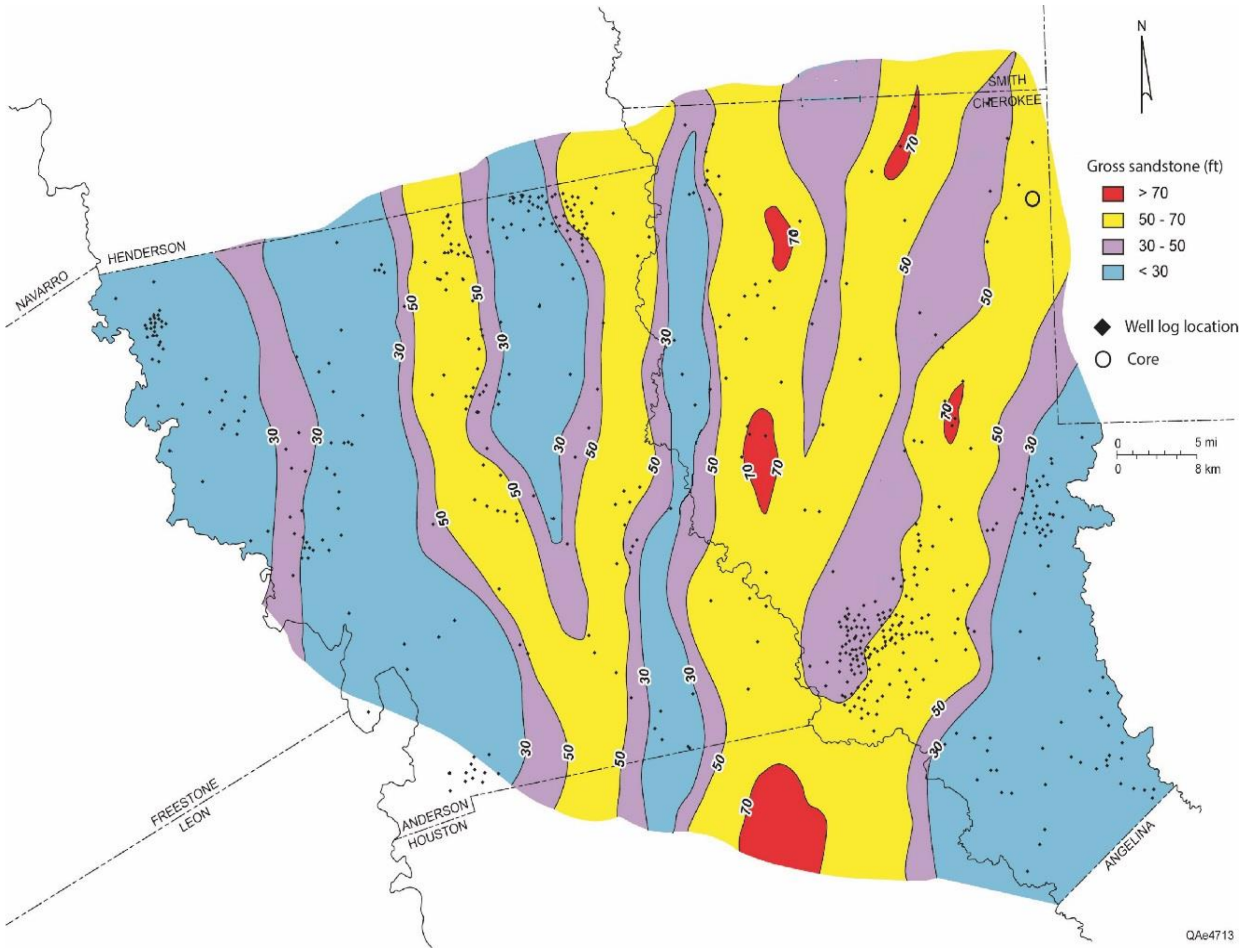

Figure 5.5: Gross-sandstone map of the Woodbine lowstand deposits of sequence 2 in Anderson and Cherokee Counties. Thickness of S2 ranges from 50 to 130 ft, consisting of the HST (30-80 ft) and LST (30-100 ft) on SP log responses.

SEQUENCE 3

Sequence 3 (S3) is bounded by MFS30 and MFS 40 (Figures 5.1 and 5.6). Thickness of S3 ranges from 55 to 120 ft on SP log responses. The HST (40-90 ft) of the S3 is formed between MFS30 at the base and SB40 at the top. On the other hand, The LST (30-120 ft) of S2 is bounded by SB40 at its base and transgressive surface at its top. The TST of S3 occurred between transgressive surface and MFS 40.

Description

Highstand systems tract

The Woodbine highstand deposits of the S3 are similar to those of sequence 1 and 2, showing an overall upward-coarsening succession between MFS 30 and SB 40 (Figure 5.1). The gross sandstone map of the HST displays elongate sandstone bodies (15-30 ft thick) with trending that merge slightly toward the center of the study area (Figure 5.7). Both northwest-southeast and northeast-southwest sandstone bodies show downdip bifurcating and slightly sinuous, narrow (2-8 km wide) tributive patterns with some small lobes (10-25 ft thick and 2-4 km wide), extending into lower gross-sandstones. In contrast with the gross-sandstone map of the HST in the sequence 1 (Figure 5.2) and 2 (Figure 5.4), more areas are characterized by low proportion of sandstones, which are 2-10 ft thick. The number of dip-elongate sandstones is less than those of the sequence 1 and 2 (Figure 5.7), reflecting less complexity of the channel framework.

Lowstand systems tract

The LST of S3 is identified by blocky to blocky-serrate SP-log profiles approximately 30-120 ft thick, similar to those of underlying sequences (Figure 5.6). Core samples display thick and poorly sorted sandstones with an erosional base, extending approximately from 3820-3855 ft (Figure 4.3). The incised valley fills slightly grade upward from pebble conglomerates and coarse-grained sandstones to crossbedded, medium-grained sandstones.

Interpretation

Highstand systems tract

The highstand deposits of sequence 3 represent fluvial-dominated deltaic facies, which is identified by overall upward-coarsening responses on SP-logs similar to those interpreted as fluvial-dominated deltaic in origin by Van Wagoner and Mitchum (1990). Moreover, the gross-sandstone map exhibits a downdip bifurcating pattern that is a main characteristic of distributary channels in delta-plain settings (Reading, 1996). The 10-25 ft thick and 2-4 km wide of small lobes in the gross sandstone map are interpreted as crevasse splays that extend across the levee and which were deposited on the floodplain as a result of levee breaching during periods of high discharge (Elliott, 1974; Reading, 1996).

Lowstand systems tract

Based on stratigraphic correlation and core samples, the LST of S3 represents incised-valley systems, characterized by thick blocky SP log responses and coarse-grained sandstones (Figure 5.6). The incised valleys were cut and contemporaneously filled by fluvial sediments throughout sea-level cycle similar to those LST of the S1 and S2.

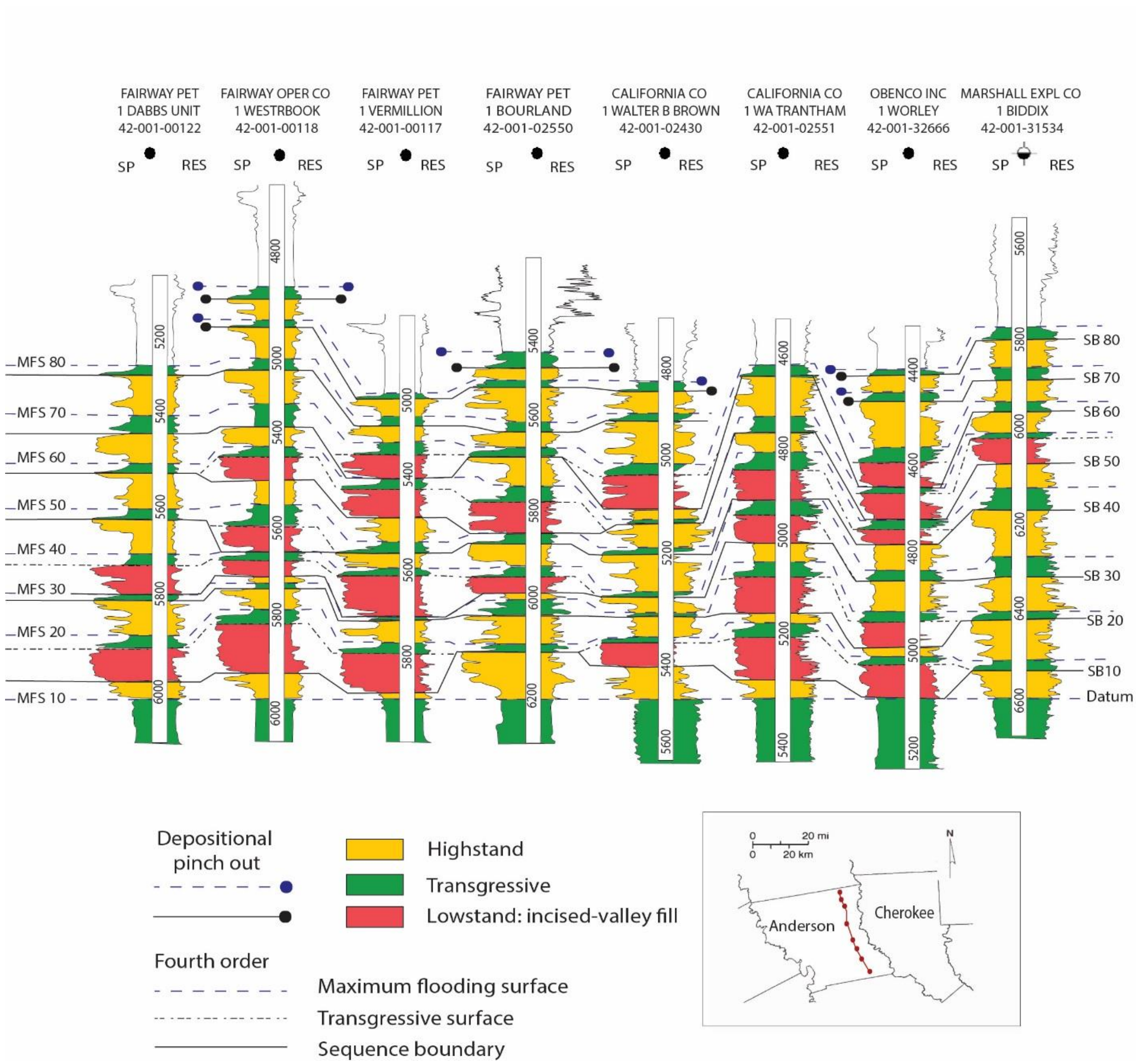

Figure 5.6: North-to-south stratigraphic section showing Woodbine fourth-order sequence correlation from well logs, representing system tracts and depositional facies of Woodbine Group. Datum is maximum flooding surface (MFS) 10.

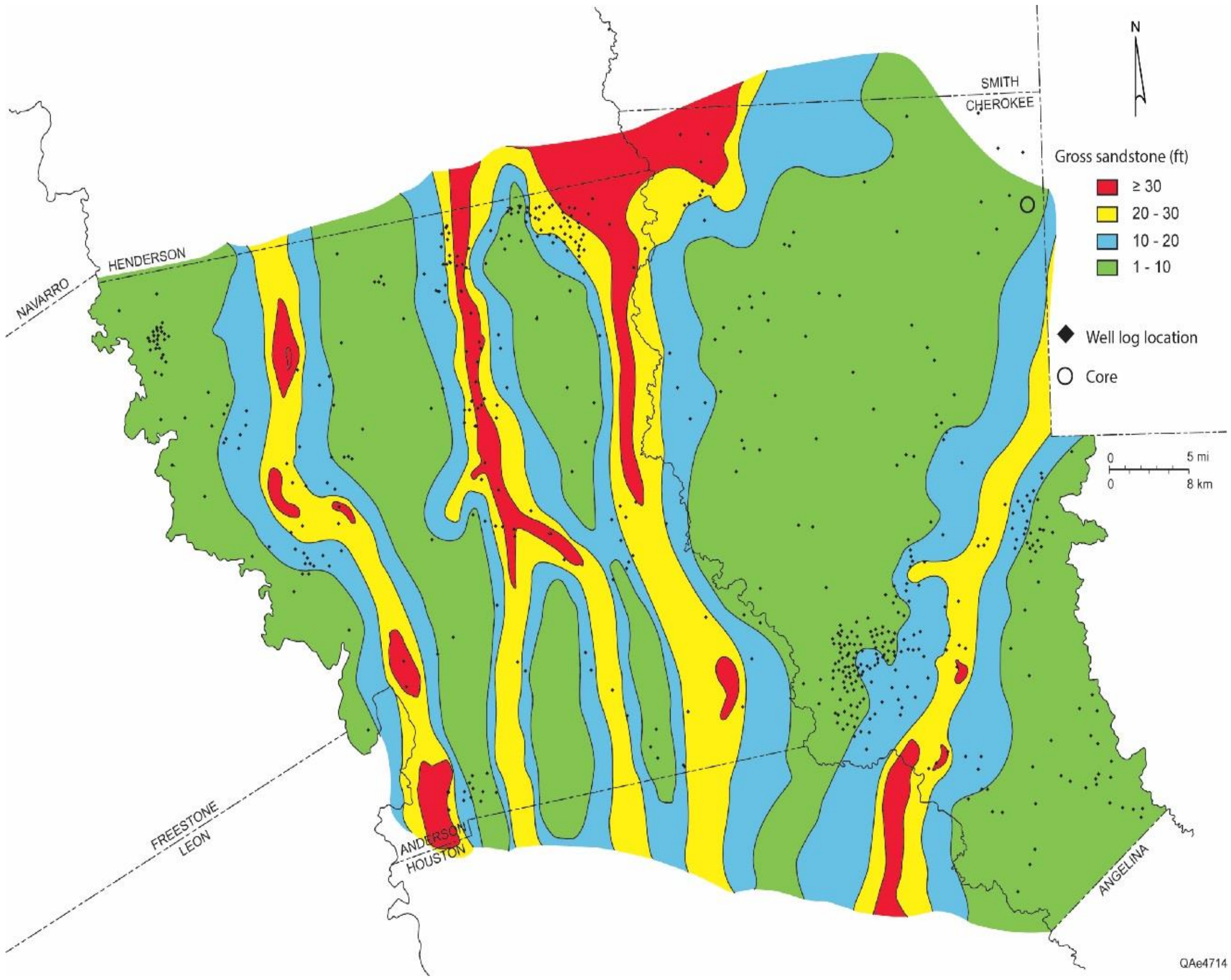

Figure 5.7: Gross-sandstone map of the Woodbine highstand deposits of sequence 3 in Anderson and Cherokee Counties. Thickness of S3 ranges from 55 to 120 ft, consisting of the 40-90 ft thick of HST and 30-120 ft thick of LST on SP log responses.

SEQUENCE 4

Description

Sequence 4 (S4) is bounded by MFS40 and MFS 50, including HST, LST, and TST (Figure 5.7). Thickness of S4 ranges from 60 to 110 ft on SP log responses. The HST (25-100 ft) of the S4 occurs between MFS40 at the base and SB50 at the top. The LST (30-80 ft) of S4 is bounded by SB50 at its base and transgressive surface at its top. The TST of S4 occurs between transgressive surface and MFS 50.

Highstand systems tract

Similar to those highstand deposits of sequence 1, 2, and 3, the highstand deposits of sequence 4 are characterized by overall upward-coarsening and serrate SP-log profiles. Based on the gross-sandstone map shown in Figure 5.8, slightly northeast-southwest-elongate sandstone bodies display downdip bifurcating patterns in Anderson County and 8-10 km wide of tributive patterns in Cherokee County. Although the distributary pattern of sandstones is similar to those of sequence 2 and 3, more areas of the HST within S4 interval are represented by muddy areas with gross-sandstone values between 5-10 ft. Moreover, bifurcated sandstones (4-5 km wide) are narrower than those of sequence 2, reaching a maximum width of 8 km. Based on core samples, the HST of sequence 2 is identified by upward-coarsening succession of interbeded siltstones and very fine to fine grained sandstone.

Lowstand system tract

Similar to those of sequence 2, the Woodbine lowstand is defined by 30-80 thick of blocky to blocky-serrate SP-log profiles, occurring between SB 40 and TS 50. The stratigraphic correlation is supplemented by core samples (Figure 4.4), representing thick and poorly sorted sandstones with pebble conglomerates and an erosional surface at its base, slightly grading upward to cross-bedded, medium-grained sandstones.

Interpretation

Highstand systems tract

The highstand deposits of sequence 4 represents fluvial-dominated delta similar to the lowstand deposits of sequence 2. Core samples of sequence 4 record delta front deposits, characterized by an upward-coarsening succession of siltstones and fine grained sandstone beds. Moreover, current ripples and soft-sediment deformation reflect a deposition from rapidly decelerating of unidirectional flows and the sediment loading (Reading, 1996). According to the gross-sandstone map in Figure 5.8, shallow and narrow channels compared with fluvial trunk channels feeding the same delta are defined as terminal distributary channels because of multiple successive splits from main channels at the very end of a distributary channel system of the delta (Olariu and Bhattacharya, 2006). However, instead of splitting main channels into terminal distributary channels, these distributary channels may join with the upward-fining successions of channel mouth bars, which may be indistinguishable from distributary channel facies (Fielding et al., 2005).

Lowstand system tract

Based on wire-line log correlation and core samples, the Woodbine lowstand deposits of sequence 4 represent an incised-valley system, a topographically elongate feature as a result of fluvial erosion. Incised valleys were simultaneously and subsequently filled with fluvial and estuarine sediments throughout the entire sea-level cycle.

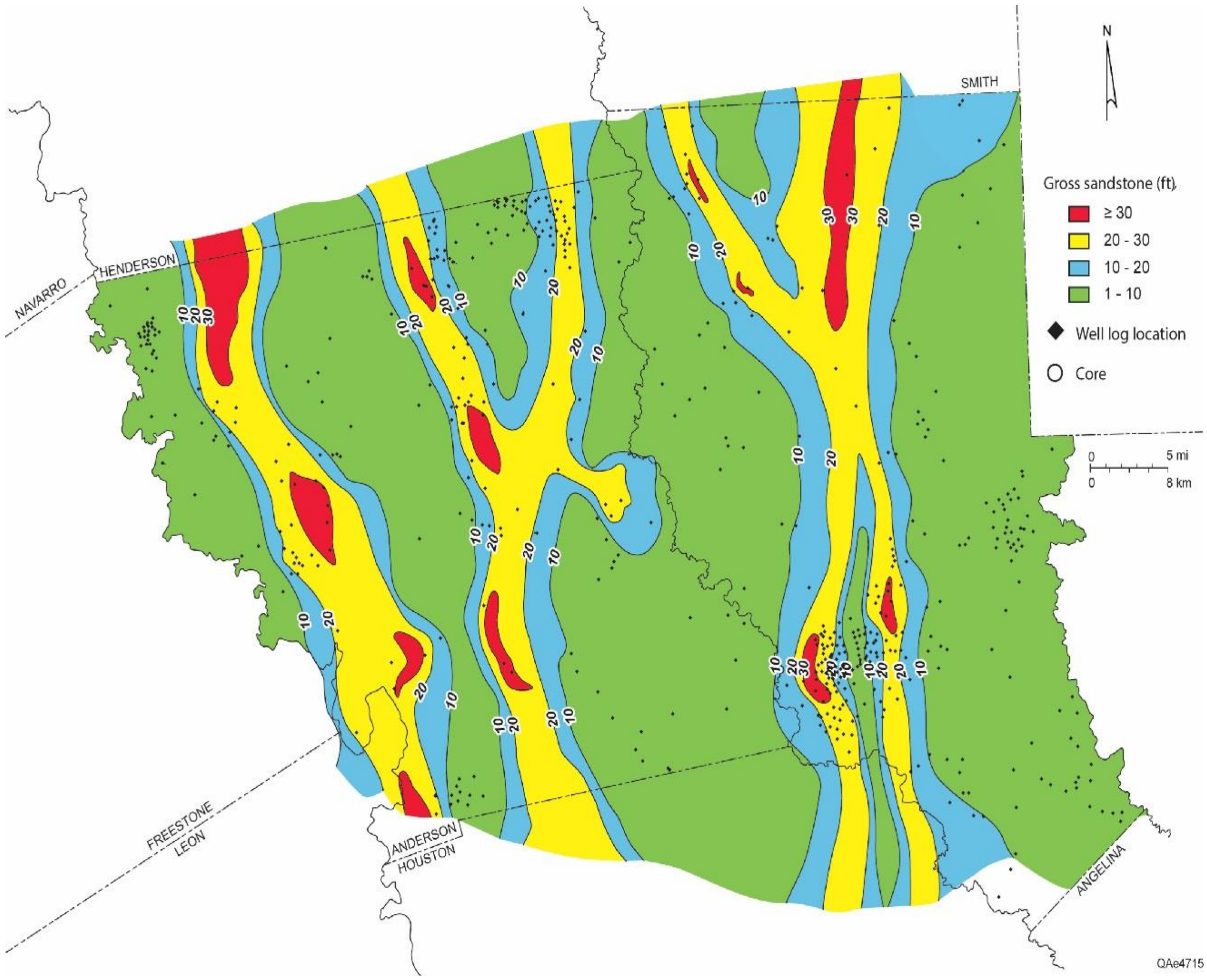

Figure 5.8: Gross-sandstone map of the Woodbine highstand deposits of sequence 4 in Anderson and Cherokee Counties. Thickness of S4 ranges from 60 to 110 ft, consisting of the 25-100 ft thick of HST and 30-80 ft thick of LST on SP log responses.

SEQUENCE 5, 6, 7, AND 8

Description

Highstand systems tract

The Woodbine highstand deposits of sequence 5, 6, 7, and 8 are similar to those of underlying sequences in term of SP-log responses and the gross-sandstone patterns. As shown in Figure 5.6 and 5.9, the SP-log responses also show an overall upward-coarsening succession with respect to overlying, blocky to upward-fining SP-log profiles in dip-elongate sandstone bodies (15-35 ft thick). The gross-sandstone map of HST of S5 (Figure 5.10) displays north-south-trending, dip-elongate sandstones. Sandstone bodies (5-10 ft thick) have distributive patterns at the central part of the study area, flanked by tributive patterns. These Woodbine highstand deposits of S5 consist of an upward-coarsening succession of very fine to fine grained sandstones with soft-sediment deformation and burrows. In contrast, the gross-sandstone map of HST of S6 (Figure 5.11) shows anastomosing and 8-10 ft wide tributive patterns similar to those of sequence 1.

Lowstand systems tract

The LST of the sequence 5, 6, 7, and 8 also have similar SP-log responses and gross-sandstone patternss. The SP-log profiles of LST also show abrupt shift of log characteristics from thick, blocky to upward-coarsening log responses. Based on the gross sandstone map of LST in the S6 interval (Figure 5.12), gross-sandstone thickness varies from 30-50 ft thick, significantly lower than those of the underlying sequences (30-120 ft thick). Gross-sandstone values are locally high in the northern part of Anderson County.

Interpretation

Highstand systems tract

Similar to the depositional system of the underlying highstand system tracts, the Woodbine highstand deposits of sequence 5, 6, 7, and 8 represent fluvial-dominated deltas. Fluvial-dominated deltas are characterized by upward-coarsening log profiles as described by Van Wagoner and Mitchum (1990). Moreover, soft-sediment deformation and burrows within upward-coarsening,very fine to fine grained sandstones reflect sediment loading on an unstable substrate, commonly encountered in shallow-marine settings that are proximal to areas of sediment input (Reading, 1996). Based on gross-sandstone maps of sequence 5 (Figure 5.10) and 6 (Figure 5.11), the change from a distributive pattern to anastomosing pattern of sandstone distributions shows that there was a frequent avulsion on low-gradent floodplains. The distributive channels in a deltaic system may also be partly anastomosing, when radial distributary channels are either interconnected or bypassed to rejoin downstream (Makaske, 2001). The anastomosing pattern of sequence 6 is similar to anastomosing rivers in Middle Holocene distributary system in the Rhine–Meuse delta, Netherlands described by Törnqvist (1993).

Lowstand systems tract

The lowstand system tracts represent incised valley systems similar to those of the underlying sequences. Incised-valley systems are characterized by thick blocky to upward-fining SP-log responses (Van Wagoner and Mitchum, 1990). Significantly low gross sandstones of S6 (Figure 5.12) show that there was low sediment supply. Accordingly, ability to transport sediments exceeded sediment supply, resulting in bypassing most of sediments to the shelf-edge delta rather than aggradation within the valleys during the regression. Although the valley was continuously filled during the transgression, most sediments are commonly siltstones and mudstones. Moreover, unlike distributive patterns of LST in the underlying sequences, the incised valleys of S6 were formed as a tributive pattern because sediment supply was not enough to approach thick channel fills, resulting in the restriction of rivers within the valleys (Holbrook and Bhattacharya, 2012).

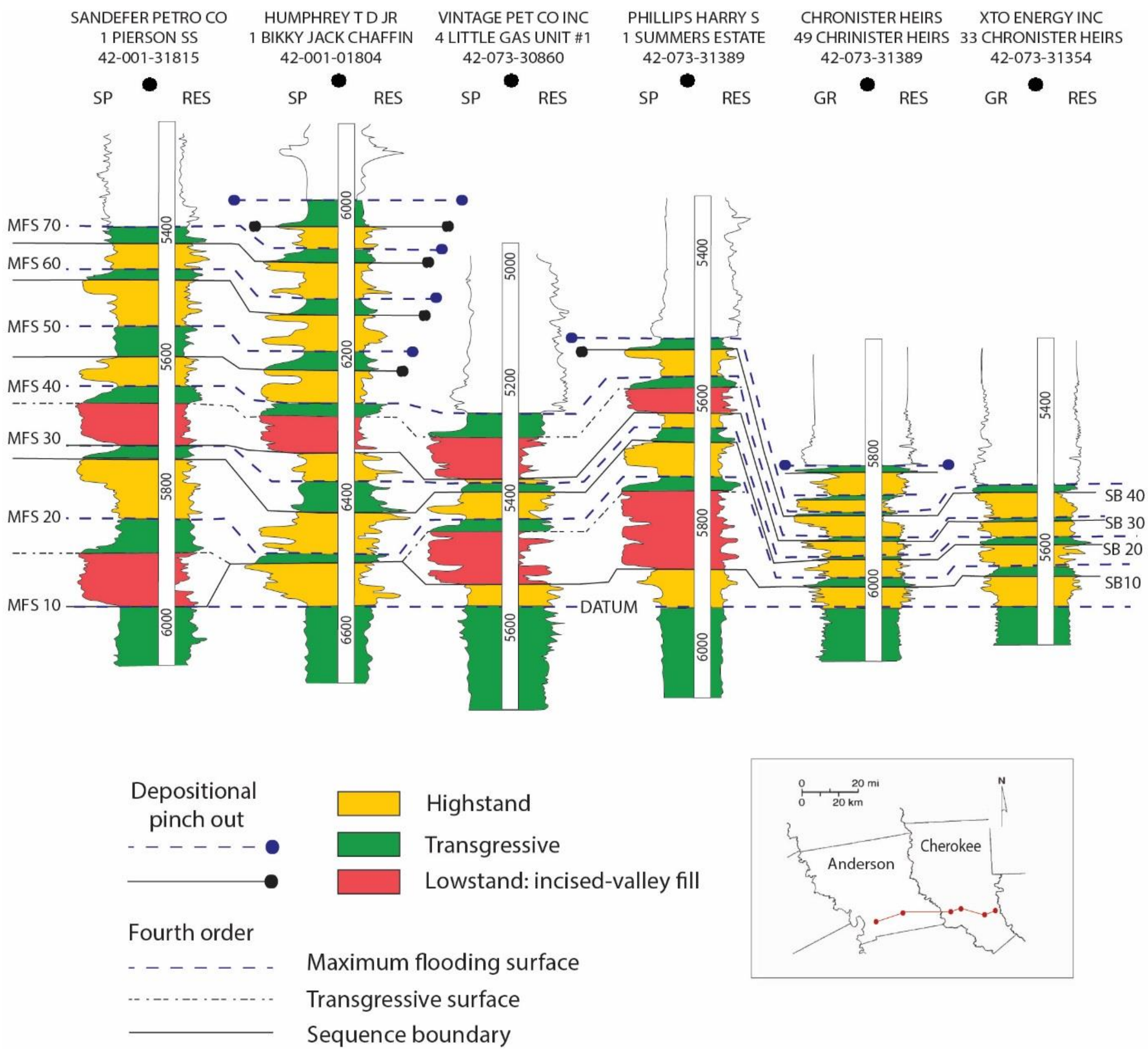

Figure 5.9: West-to-east oriented stratigraphic section with Woodbine fourth-order sequence correlation from well logs, representing system tracts and depositional facies of Woodbine Group. Datum is maximum flooding surface (MFS) 10.

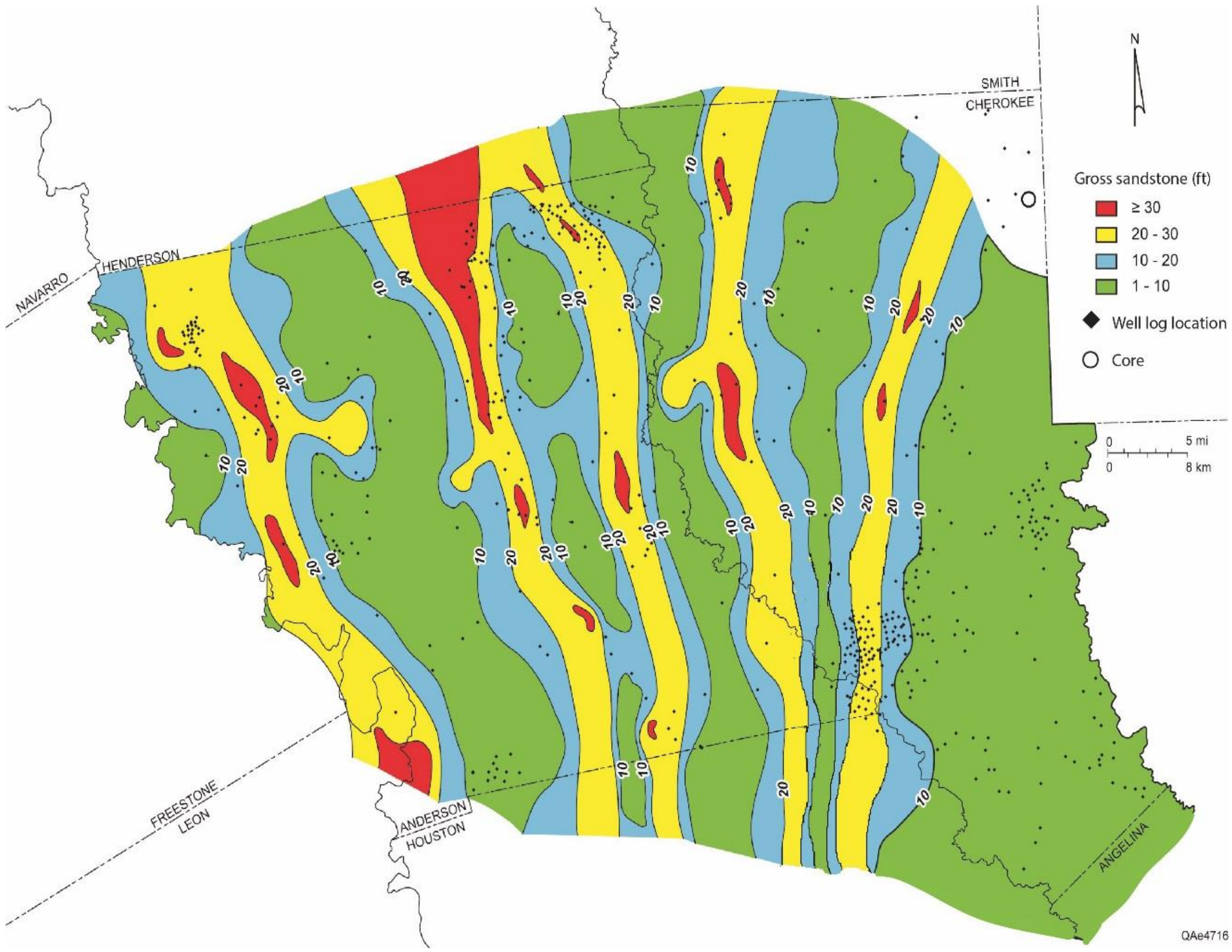

Figure 5.10: Gross-sandstone map of the Woodbine highstand deposits of sequence 5 in Anderson and Cherokee Counties. Thickness of S5 ranges from 55 to 120 ft, consisting of the 50-100 ft thick of HST on SP log responses.

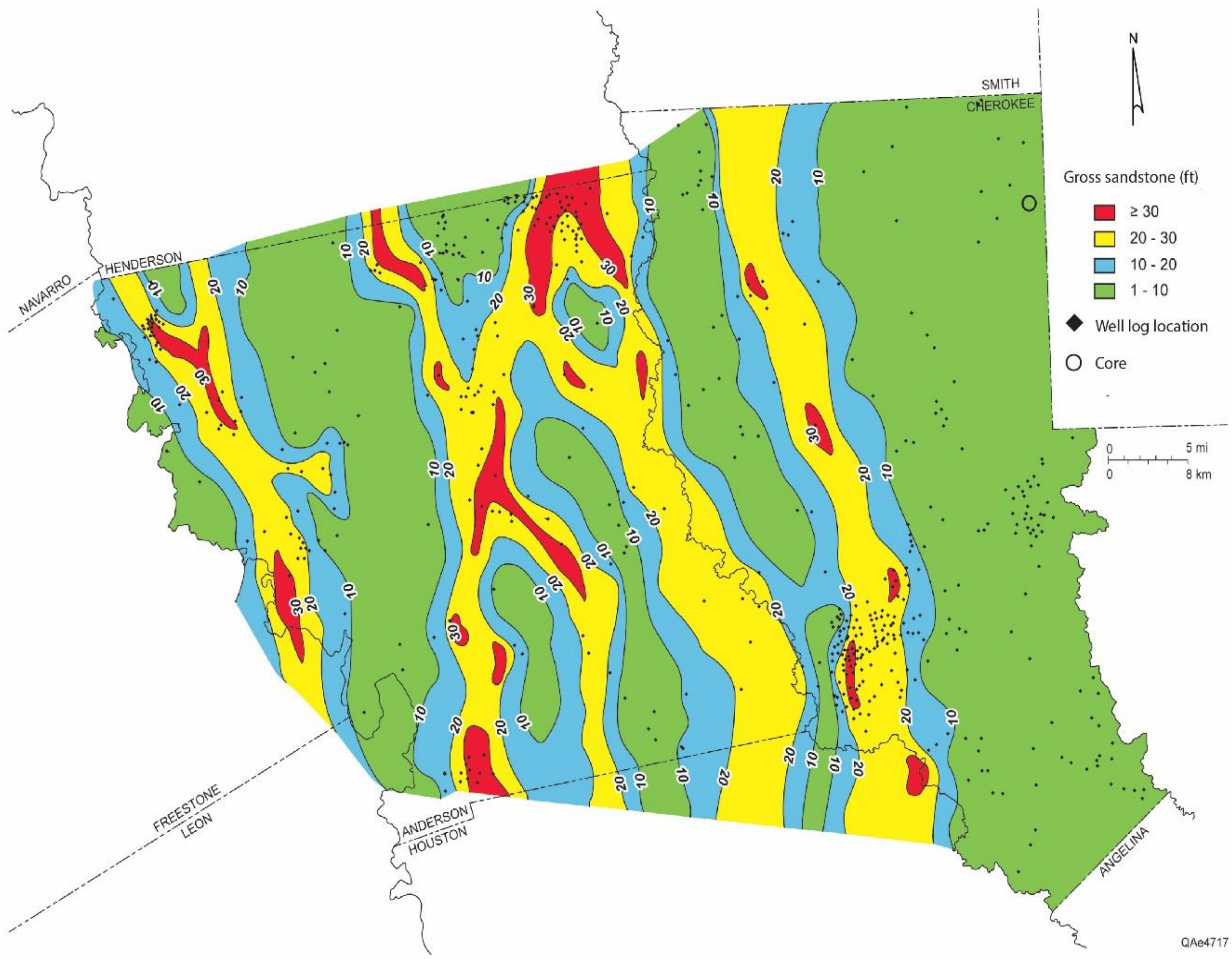

Figure 5.11: Gross-sandstone map of the Woodbine highstand deposits of sequence 6 in Anderson and Cherokee Counties. Thickness of S6 ranges from 45 to 100 ft, consisting of the 25-80 ft thick of HST and 30-100 ft thick of LST on SP log responses.

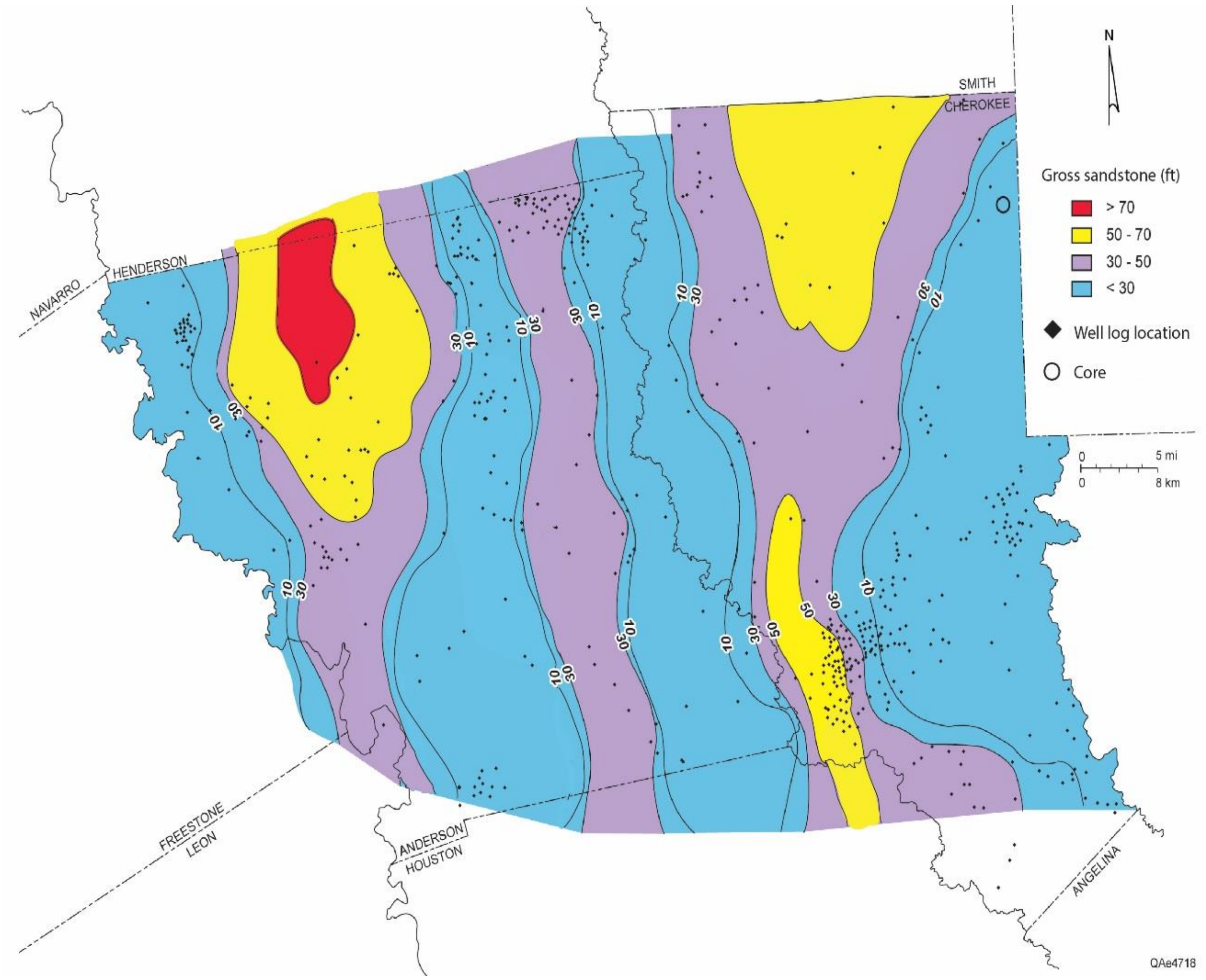

Figure 5.12: Gross-sandstone map of the Woodbine lowstand deposits of sequence 6 in Anderson and Cherokee Counties. Thickness of S6 ranges from 45 to 100 ft, consisting of the 25-80 ft thick of HST and 30-100 ft thick of LST on SP log responses.

SEQUENCE 9

Description

Sequence 9 (S9) is bounded by MFS90 and MFS 100, including HST, LST, and TST (Figure 5.14). Thickness of S9 ranges from 40 to 120 ft on SP log responses. The HST (25-80 ft) of the S4 occurs between MFS40 at the base and SB50 at the top.

Highstands system tract

Unlike the underlying sequences, most of the study area in the S9 interval exhibits lesser values of gross sandstone ranging from 10-20 ft. Sandstone accumulation is confined to narrow and slightly sinuous streams with the north-south trend and extended to unconfined areas, and massive lobes of sandstone accumulation within the east-west trend. Further to the southern part of the study area, sandstones accumulated as isolated barriers along an east-west-trending depositional axis. The widths of these east-west-oriented barriers are narrower than those of massive lobes.

Base on stratigraphic correlation in Figure 5.14, the narrow, north-south oriented sandstones are defined by upward-coarsening SP-log responses within 20-30 ft thick sandstone beds. The unconfined sandstone accumulation and southern sandstones are characterized by thick (>30 ft) blocky and slightly upward-coarsening wireline log patterns. However, most of the map area shows low gross sandstones with serrate log profiles.

Interpretation

Highstand systems tract

In contrast to the underlying sequences, the S9 interval strongly experience wave influence rather than fluvial or tidal influence based on sequence correlation from well logs and gross-sandstone maps with no core data. According to the gross-sandstone map of the S9 (Figure 5.13), the depositional system of the S9 changes from fluvial systems to marine systems, characterized by much thicker of aggraded sandstones nearshore area and sand barriers. Sediments were transported seaward through the distributary channels on the delta plain and eventually reworked by wave processes, resulting in massive, strike-aligned deposition with arcuate to cuspate shape along the shoreline based on both thick (>30 ft) blocky and slightly upward-coarsening SP-log characters and great gross-sandstone thickness (20-35 ft thick). This depositional system is identified as the wave-dominated delta, reworked by longshore currents of wave regime. During the late stage of sea-level rise, the high rate of sediment supply can rival the retreat of shoreline and new accommodation, resulting in progradation (Catuneanu, 2006). However, the rate of progradation tend to be slower in the wave-dominated delta than that in a fluvial-dominated delta because the sediments that transported to the river mouth of the wave-dominated delta were carried away by longshore currents (Bhattacharya, 2006). Accordingly, rivers in this wave-dominated delta enable to maintain the higher gradient, limiting avulsion. Because of the high gradient of the slope, the avulsion of distributary channels may be restricted, resulting in a few number of active distributary channels as described by Bhattacharya (2006). As seen in Figure 5.13, the number of distributary channels is less than those of previous sequences. Furthermore, the thick blocky to slightly upward-coarsening SP-log responses are interpreted as sand barriers, deposited and reworked by wave process. Based on stratigraphic aspect and depositional regime, the depositional system of the S9 that the deltaic system is principally controlled by wave process with a minimal of fluvial or tidal influence is similar to the São Francisco delta (Bhattacharya, 2006).

In conclusion, the transporting process of Woodbine succession was changed from fluvial regime of fluvial-dominated delta of the underlying sequence to wave regime of wave dominated delta of sequence 9. The regime change at the delta front may be caused by the evolution of RSL cycle. During RSL fall, the shelf is still wide, resulting in strongly river influence on inner- to mid-shelf deltas. However, deltas tend to be transformed into a barrier-island system or reworked by wave process during the early stage of the lower frequency relative sea-level (RSL) rise.

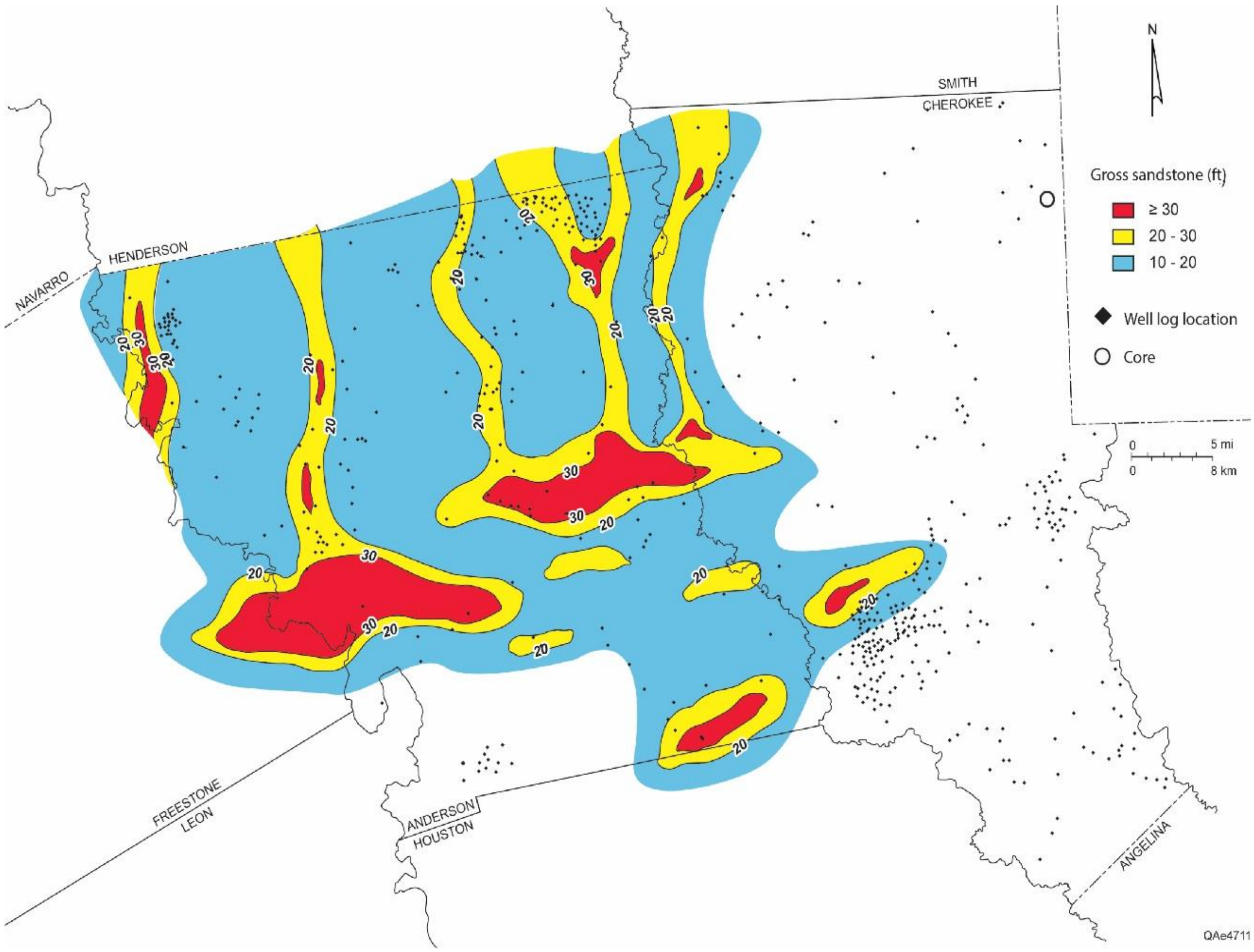

Figure 5.13: Gross-sandstone map of the Woodbine highstand deposits of sequence 9 in Anderson and Cherokee Counties. Thickness of S9 ranges from 40 to 120 ft, consisting of 25-80 ft thick of HST on SP log responses.

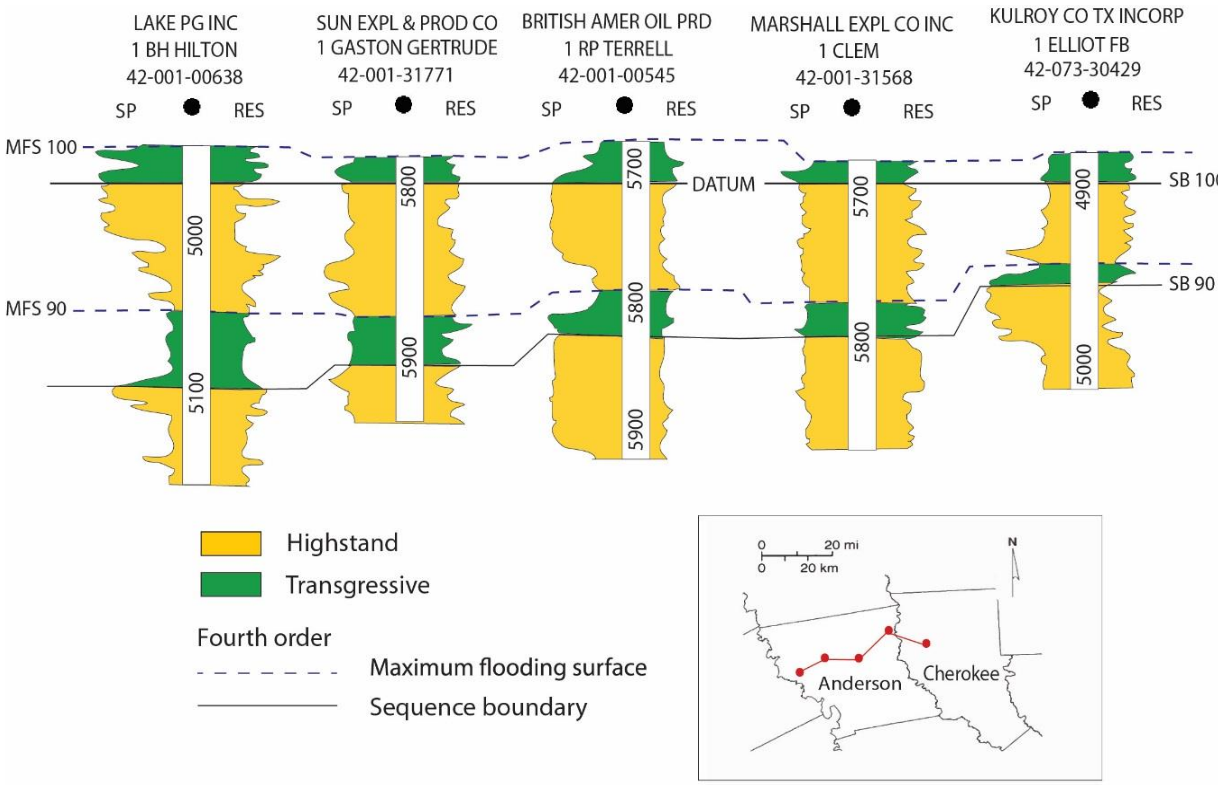

Figure 5.14: West to East oriented of the Woodbine fourth-order sequence correlation from well logs, representing system tracts and depositional facies of sequence 9. Datum of the sequence correlation is sequence boundary (SB100).

SEQUENCE 10, 11, 12, 13, AND 14

Description

Highstand systems tract

Sequence 10, 11, 12, 13, and 14 consist of two principal log facies similar to those of sequence 9, which are upward-coarsening to serrate and blocky to upward-coarsening SP-log responses (Figure 5.15). Most of the study areas are characterized by low-gross sandstones with serrate log profiles. However, the thickness and gross-sandstones of each sequence decrease upward.

Interpretation

Highstands system tract

Based on SP-log character, the HST of sequence 10, 11, 12, 13, and 14 consist of 20-30 ft thick of blocky to upward-coarsening SP-log responses similar to those of sequence 9. These blocky to upward-coarsening SP-log profiles represent wave-dominated deltas and sand-barriers as those described by Van Wagoner and Mitchum (1990). Moreover, upward-thinning of the Woodbine fourth-order sequences in response to low sediment supply, contributed to a basinwide sea-level rise during the third-order transgressive period similar to the upper Woodbine Group in the southwestern part of the East Texas basin documented by Hentz et al. (2014). During the sea-level rise, great sediment influx is required to maintain delta progradation in order to fill an increase accommodation space. However, the upward-thinning of the Upper Woodbine Group (Lewisville Sand) implies a low sediment supply, resulting in a landward migration of the shoreline and wave-reworked sediments. When deltaic sediments are completely redistributed by longshore currents, deltas tend to form barrier-islands and strandplains, which are defined by the blocky and serrate SP-log responses, similar to those described by Fisher, 1969.

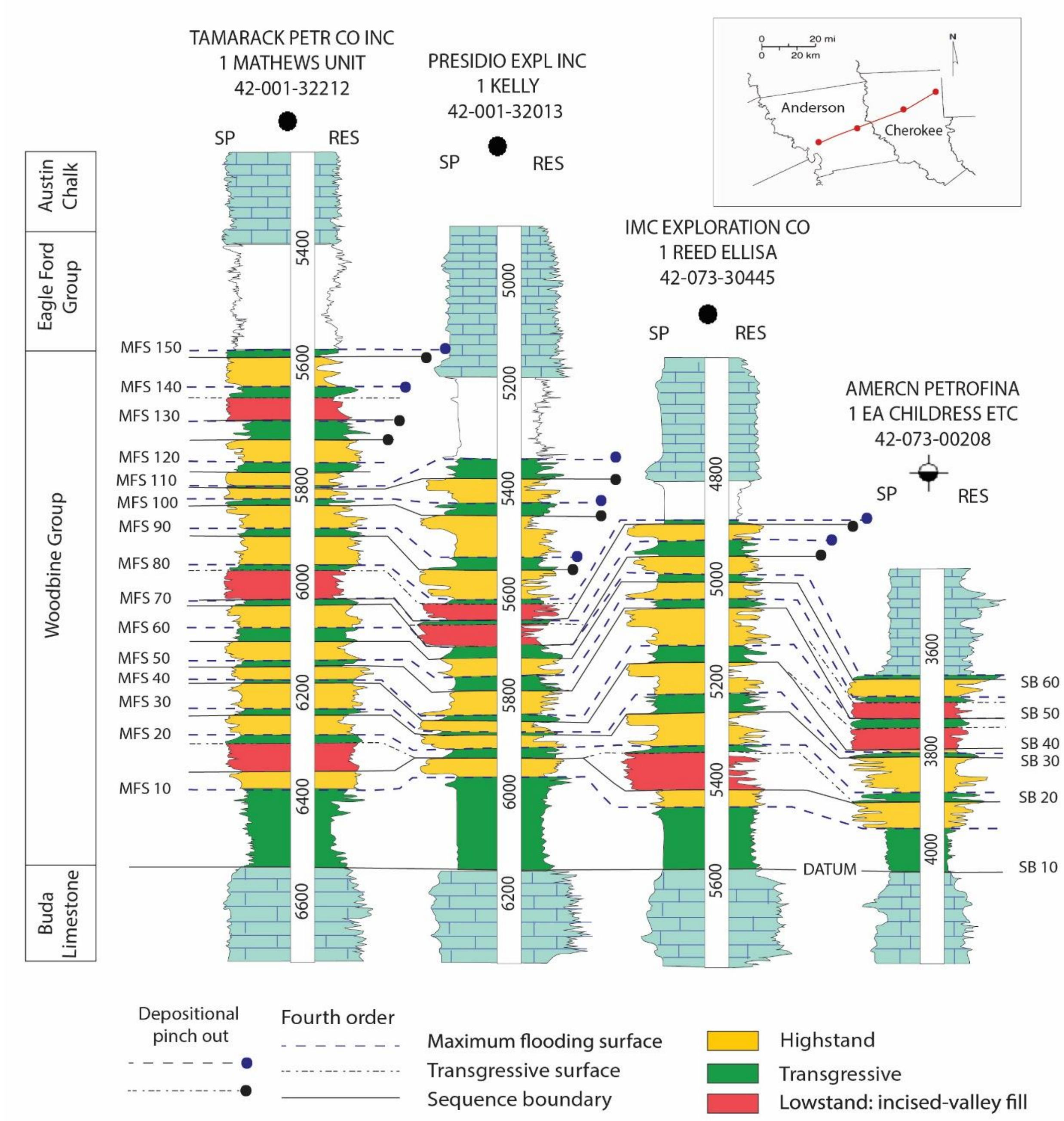

Figure 5.15: West–to-east oriented stratigraphic section showing Woodbine fourth-order sequence correlation with multiple depositional pinch outs at the top of the Woodbine Group toward the Eagle Ford Group and Austin Chalk. Datum is sequence boundary (SB) 10.

Chapter 6: Discussion

Depositional history of the Woodbine Group in Anderson and Cherokee Counties

Depositional systems of the East Texas Basin were significantly controlled by local sea-level fluctuations because of differential subsidence and uplift during Mesozoic period (Ewing, 1991b). Owing to widespread subsidence from the early Cretaceous to the earliest late Cretaceous, marine limestone unit known as Buda Limestone covered the shelf of the East Texas Basin. In the mid-Cenomanian, the major relative sea-level fall in response to the uplift at the southern part of the Mississippi embayment terminated subsidence and exposed the shallow shelves and platforms around the flanks of the basin, causing a regionally extensive unconformity (SB 10) at the top of Buda Limestone. SB 10 is overlain by Maness Shale, which is in turn overlain by the Woodbine Group during late Cretaceous time (Figure 6.1) (Salvador, 1991).

The Woodbine succession formed as a third-order lowstand systems tract during the overall sea-level fall, which was episodic and punctuated by higher frequency sea-level cycles. The Woodbine succession can be subdivided into LST, HST, and TST of forth-order sequences with a maximum of 14 cycles along the basin axis, each representing 110 k.y. (Ambrose et al., 2009). In the eastern part of the study area, gradual depositional pinch outs caused a decrease of the fourth-order sequences of the Woodbine Group toward the Eagle Ford Group and Austin Chalk, where the Eagle Ford deposits is absent due to the Sabine Uplift (Figure 5.15).

Lowstand System Tract

Lowstand systems tract of the Woodbine succession formed during a period of sea-level fall, still stand, and early stage of sea-level rise on sequence boundaries.

Sequence boundaries (SBs) were initially formed by fluvial incision during sea-level fall. They are preserved at the base of incised valley fills and truncate the underlying highstand systems tract. These surfaces were locally exposed along the length of the incised valley and never completely served as bypass surfaces because valleys were cut, modified, and buried locally throughout the regressive and transgressive cycle (Figure 6.2 and 6.3), similar to the late Pleistocene-Holocene Tiber delta succession as described by Milli et al. (2016). Accordingly, these SBs are time-transgressive surfaces, recording cumulative scours as described by Holbrook and Bhattacharya (2012). During early and late lowstand periods, incised valleys were partially covered by a multistoried thick, poor-sorted, coarse-grained sandstones with pebble conglomerates, recording an abrupt shift of facies across a regional erosional surface, similar to that described by Van Wagoner and Mitchum (1990).

During the early Late Cretaceous, salt mobilization in the East Texas Basin created more basin accommodation (Seni and Jackson, 1984), coinciding with the influx of abundant coarse-grained sediments from the north margin of the Gulf Coast Basin (Ambrose et al., 2009). Because of more accommodation space, Woodbine incised-valley fills are preserved during relative sea-level fall (Ambrose et al., 2009; Hentz et al. 2014) similar to the lower Tuscaloosa Formation at east of the Sabine Uplift (Woolf, 2012). Moreover, because the high sediment supply exceeded the ability to transport sediment, rivers tended to aggrade sediments. A river pattern was changed from the low-sinuosity of a braided river in the upstream to high sinuosity of a meandering river in the downstream, reflecting a decrease of the gradient profile. When fluvial sediments in downdip reached the channel fills and were not confined within valleys, they tend to disperse radially through distributary system (Holbrook and Bhattacharya, 2012).

Although distributive patterns of LST are common, the LST of sequence 6 shows tributive patterns with significantly low gross-sandstone content, compared to the underlying sequences, recording restricted rivers within valleys.

During sea-level fall, incised-valley extended southwestward to the inner shelf and transported sediments to the Upper Cretaceous shelf-edge, forming shelf-edge deltaic systems (Ambrose et al., 2012). The woodbine shelf-edge is located in northern Tyler and southeastern Polk Counties, recognized by shelf-to-slope transitional deposits (Ambrose et al., 2014).

Transgressive systems tract

Transgressive systems tracts were developed during sea-level rise and are characterized by upward-fining responses on GR and SP log profiles and a retrogradational stacking pattern of fine-grained sediments as observed in core. During sea-level rise, incised valleys were filled with fluvial deposits that are fine-grained sediments with less amalgamation. Channels within TST were commonly separated by floodplain with low lateral amalgamation, as a result of the rate of accommodation space having exceeded sediment supply. Moreover, the thickness of channels also decreases upward from 20-30 ft at the lower part of the incised-valley to 10-15 ft at the upper part of the incised valley. As transgression continues, estuarine conditions may migrate landward from the seaward end of the valley (Boyd et al., 2006).

Highstand systems tract

Highstand systems tracts were formed during the late stage of sea-level rise. When sea-level rise decreased, sediment supply exceeded new accommodation space, resulting in seaward progradation of deltaic systems. The Woodbine highstand deposits of sequence 1 to 8 represent fluvial-dominated deltaic deposits, characterized by upward-coarsening SP-log responses as described by Van Wagoner and Mitchum (1990). Deltaic deposits are commonly recorded as upward-coarsening succession as a result of superposition of sandy distributary-channel and channel-mouth-bar facies onto muddy delta-front facies.

As documented on HST gross-sandstone maps of each successive sequence in this study, channel systems of fluvial-dominated deltas are commonly expressed in two patterns, including anastomosing and distributive patterns. HST deposits of sequence 1 (Figure 5.2) and 5 (Figure 5.8) represent fluvial–dominated deltas with anastomosing channel systems. An anastomosing pattern in a fluvial-deltaic system tend to form as a part of distributive channels when the channels are interconnected by frequent avulsions and slow abandonment of old channels under a low gradient condition similar to Rhine-Meuse delta in Netherlands as described by Törnqvist (1993). In contrast, the other HST sequences represent distributive patterns, for which a channel trunk was forced to bifurcate downdip.

Unlike the underlying sequences, the HST deposits of sequence 9 to 14 represent wave-dominated deltas and coastal barriers, characterized by blocky to upward-coarsening and serrate SP-log responses. Most areas were covered by muddy deposits with serrate log profiles, reflecting low gross-sandstones. Accordingly, the avulsion of distributary channels was limited, causing a few number of active distributary channels, compared to fluvial-dominated deltaic deposits. Moreover, the upward thinning of the fourth-order sequences from sequence 9 to 14 corresponds to a continuously low sediment supply and accommodation during the third-order transgressive system tract as those described by Hentz et al. (2014).

During sea-level rise, delta-front deposits typically reworked by wave processes, resulting in strike-aligned deposition and barrier-island system (Porebski and Steel, 2006; Blum and Roberts., 2012). During this time, the basin continuously experienced major subsidence, leading to the deposition of the Tertiary strata (Ewing, 1991a, b).

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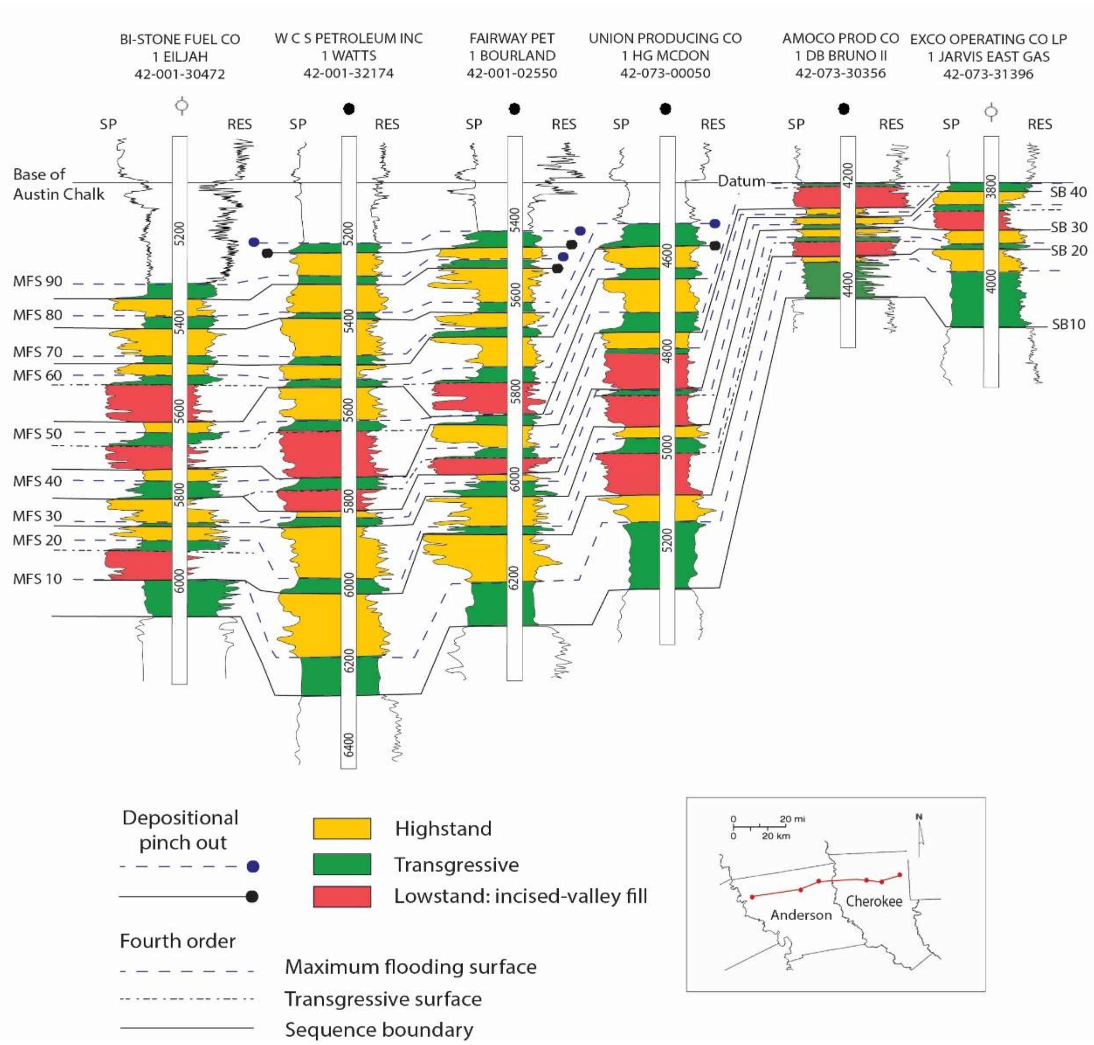

Figure 6.1: West–east-oriented stratigraphic section displaying Woodbine fourth-order sequence correlation with multiple depositional pinch outs at the top of the Woodbine Group toward the Eagle Ford Group and Austin Chalk. Datum is the base of Austin Chalk.

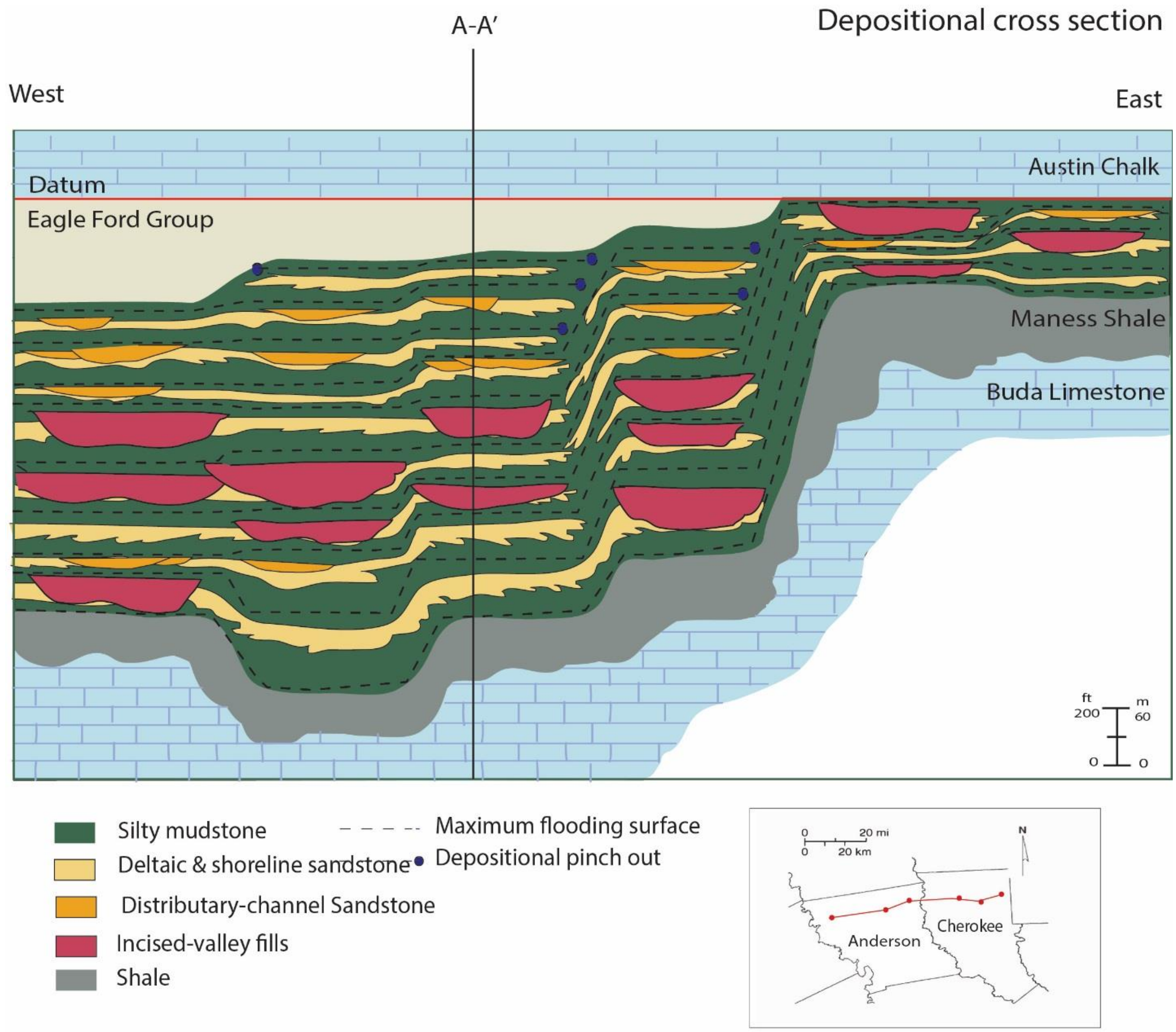

Figure 6.2: Regional east-west cross section from the six wells in Figure 6.1., illustrating facies distribution and systems-tract framework of Woodbine Group. Datum is the base of Austin Chalk.

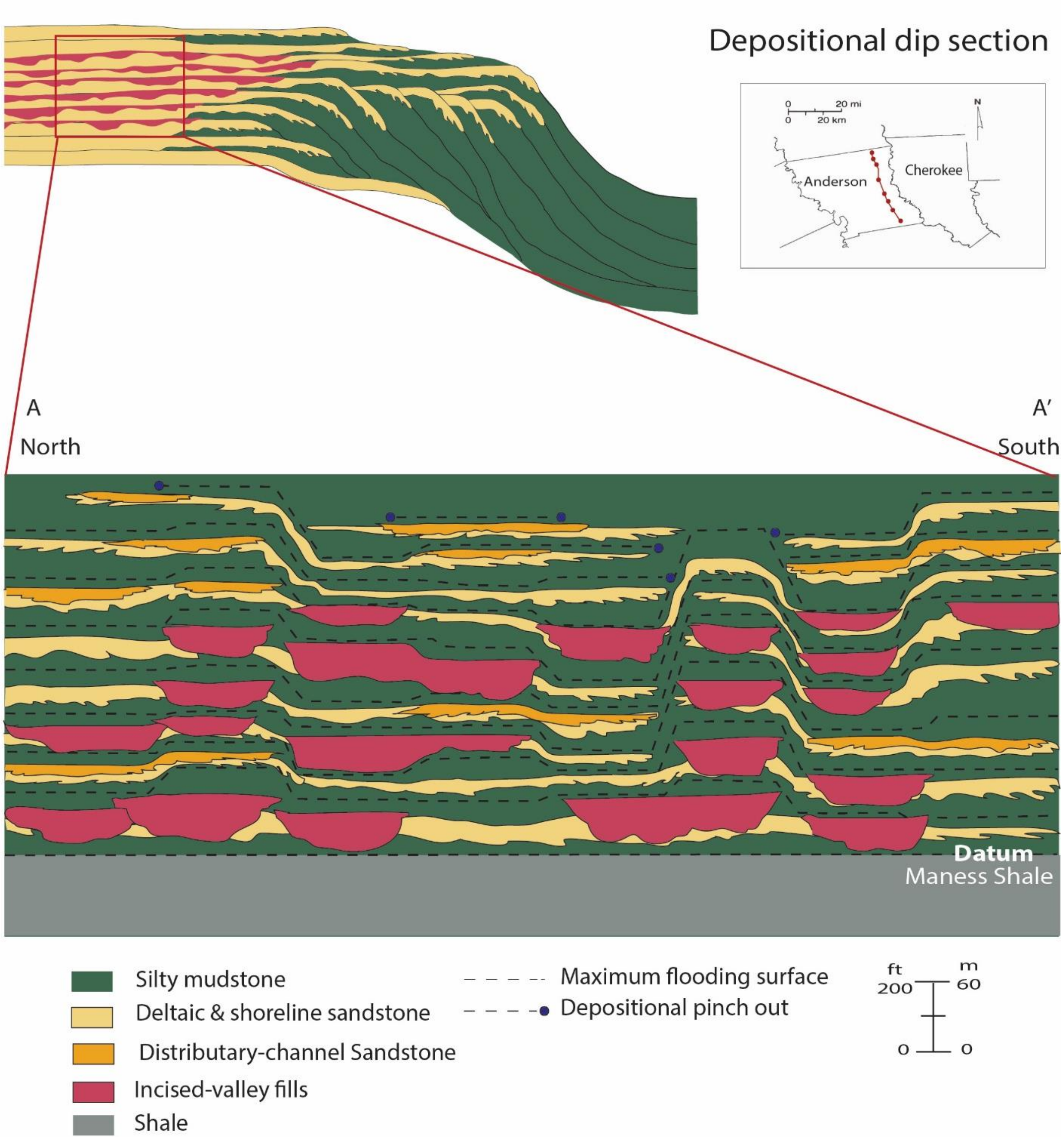

Figure 6.3: Regional north-south dip section from the eight wells in Figure 5.6, illustrating facies distribution and systems-tract framework of Woodbine Group. Datum is maximum flooding surface (MFS) 10.

Chapter 7: Conclusions

- Fourth-order sequences of the Woodbine Group in Anderson and Cherokee Counties consist of highstand, lowstand, and transgressive deposits with a maximum of 14 cycles along the basin axis, decreasing in number westward to the Woodbine outcrop and eastward to the Sabine Uplift with a maximum of 6 cycles and 3 cycles, respectively. A decrease of the number of the fourth-order sequences in the Woodbine Group is a result of depositional pinchouts at the top of Woodbine succession eastward onto the western margin of the Sabine Uplift, in areas of lesser basin subsidence and accommodation.

- Depositional systems of the Woodbine Group in Anderson and Cherokee Counties illustrate a lateral variation from a highstand deltaic system to incised-valley system in response to relative sea-level, differential subsidence, and uplift. Moreover, the vertical lithofacies express a variation between prodelta, delta front, and distributary channels that truncating into the underlying deltaic deposits.

- From sequence 1-8, Woodbine highstand deposits typically consist of overall upward-coarsening successions of fluvial-dominated deltaic deposits composed of distributary channel, crevasse splay, and delta front deposits. These Woodbine highstand deposits are truncated by incised-valley fills during sea-level fall, composed of poorly sorted, coarse-grained sandstones and pebble conglomerates.

- Unlike sequence 1-8, Woodbine highstand deposits of sequence 9-14 represent strike oriented (east-west-trending) sandstone bodies in gross-sandstone maps.

These highstand deposits are thick (>30 ft) and have blocky with slightly upward-coarsening SP responses. They are interpreted as wave-dominated deltas and isolated barriers. Based on strike-aligned deposition of gross-sandstone bodies and blocky to upward-coarsening SP-log character, sandstone-body geometry is inferred to have been controlled principally by wave rather than fluvial processesduring early stage of sea-level rise.

- Woodbine lowstand deposits are dominated by incised-valley deposits. The formation of incised-valleys in the Woodbine Group was enhanced by salt mobilization and high sediment supply from the north margin of the Gulf Coast Basin Because of the sediment influx, sediments were aggraded and reached its channel fills, resulting in the formation of distributary systems during sea-level fall.

- Upward decreases of both fluvial influence and thickness of each Woodbine fourth-order sequences record major transgression of third-order transgressive system tracts.

- The potential reservoirs of HST within sequence 1-8 occurred in the high degree of heterogeneity of the fluvial-dominated deltaic system, where discontinuous distributary channels and crevasse-splay pinch out into interdistributary deposits, resulting in high volumes of unproduced oil within the reservoirs. In contrast, the potential reservoirs within HST of sequences 9-14 are strike-oriented sandstone bodies and sand barriers that were reworked by wave regime along a northeast-southwest trend.

- The potential reservoirs of LST within the Woodbine Group show high continuity of the fluvial successions within incised-valleys, consisting of coarse-grained sandstones and pebble conglomerates.

- The low lateral continuity of reservoirs within TST of the Woodbine succession is formed as a result of low lateral amalgamation of channels, commonly separated by floodplain mudstones.

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